



# Analysis of solderability test methods: prediction model generation for through-hole components

Bobby Woods

## Publication date

01-01-2013

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**UNIVERSITY of LIMERICK**

**OLLSCOIL LUIMNIGH**

**Analysis of Solderability Test Methods:  
Prediction Model Generation for Through-Hole Components**

**Author: Bobby Woods**

**0010057**

**A Thesis Submitted for the Degree of**

**Doctor of Philosophy**

**To**

**The College of Engineering,**

**Department of Design and Manufacturing Technology,**

**University of Limerick,**

**Ireland.**

**Research Supervisor - Dr Christy Gillick**

**Submission**

**March 2013**

## Declaration

I declare that this thesis has not already been accepted in substance for any degree and is not currently submitted in candidature for any other degree.

.....

(Bobby Woods)

Date:.....

.....

(Dr. Christy Gillick)

Date:.....

## Statement

I affirm that the substance of this degree is currently the result of my own investigation and that due reference and acknowledgement is made where necessary to the work of other researchers.

.....

(Bobby Woods)

Date:.....

.....

(Dr Christy Gillick)

Date:.....

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## **Dedication**

This thesis is dedicated to my wife Catriona for her encouragement and support during the project for which I am grateful. To my parents Bobby, Kathleen and all my family who stood by me all these years and provided me with a wealth of knowledge and lifelong experiences.

## **Acknowledgements**

I would like to thank my supervisor, Dr Christy Gillick, who provided me with great support and advice when I faced the inevitable barriers along the way, and also Dr Alan Ryan for his advise and proof reading of the project, I am truly grateful.



## Abstract

In order to achieve a reduction in solderability related defects on electronic components and Printed Circuit Board's (PCB's) in electronics manufacturing, preventive controls such as "Dip & Look" and "Wetting Balance" solderability testing need to be fully optimised to screen out all poor soldering components and PCB's. Components and PCB's that pass these tests should solder correctly in volume production.

This thesis initially investigates the variations and effects of the Dip & Look solderability test on components and PCB's. Data from this analysis proved that no matter how extreme the oxidation on the component termination or PCB pad, the visual inspection criteria of 95% solder coverage is achieved each time. Dip & Look testing therefore serves no useful purpose to the electronics mass manufacturer in determining the solderability of a component or PCB.

The second option available to screen components is the Wetting Balance Test. Due to the variation of parameter settings within the international standards for solder temperature, immersion speed, immersion depth, removal speed and dwell time, a complete analysis was required to determine the optimum settings for the MUST II Wetting Balance machine that would detect poor soldering components.

The test specifications vary considerably between all the international standards. Design of Experiments conducted an in-depth analysis to determine the optimum Wetting Balance test settings using the range of test specifications stated within the standards. Within the range of specifications the least stringent and most stringent settings were developed which highlighted the difference in results when testing at the lower end and higher end of the current international standards.

Prediction models were generated for each of the responses ( $T_a$ ,  $T_b$ ,  $F_{max}$ ,  $TF_{max}$ ,  $F_1$  and  $F_2$ ) using Wetting Balance machine parameters solder temperature, immersion speed and immersion depth. To test these models, components with a history of solderability issues were tested and evaluated using the least stringent and most stringent settings. XRF measurements were conducted to ensure uniform plating thickness. Both components passed the Wetting Balance test criteria generated by the model equations using the least stringent settings but failed when using the most stringent settings. The current industrial specification for  $T_a$  ( $<0.6$  seconds) and  $T_b$  ( $<1$  second) were also achieved on both components even though the components had known soldering issues on a series production line. It was proven that there was a 40% difference in the  $T_a$  and  $T_b$  values when testing at the lower end of the international specification as opposed to testing at the higher end of the specification, which questioned the spread on the tolerance of the parameter settings within the current international standards. It was established through experimentation that the current  $F_1$  criteria, which states no less than 50% of  $F_{max}$ , must be reviewed based on the analysis carried out in this thesis.

To ensure completeness a component with no soldering issues was also tested using the same procedure. This component passed the Wetting Balance test using the least stringent and most stringent settings illustrating that the settings derived through this research are robust to detect good and poor soldering components.

This research has developed an alternative set of Wetting Balance test specifications and has defined new model equations that will predict the Wetting Balance responses such as  $T_a$ ,  $T_b$ ,  $F_{max}$ ,  $TF_{max}$ ,  $F_1$  and  $F_2$ , which will result in components which are deemed acceptable under international and industrial standards.

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## Notation

Notation	Explanation	Units
C	Constant	
DoE	Design of Experiment	
ELV	End of Life Vehicle	
EU	European Union	
F1	Force after two seconds	mN
F2	Force after five seconds	mN
Fmax	Maximum force	mN
HASL	Hot Air Solder Levelling	
I <sub>s</sub>	Immersion Speed	mm/sec
I <sub>D</sub>	Immersion Depth	mm
NiAu	Nickel Gold	
P	Perimeter	mm
PCB	Printed Circuit Board	
PDCA	Plan Do Check Act	
PPM	Parts per Million	
PTH	Plated Through Hole	
QFP	Quad Flat Pack	
QPR	Quality Problem Report	
R	Rosin	
RA	Rosin Activated	
RMA	Rosin Mildly Activated	
RoHS	Restriction of Certain Hazardous Substances	
SAC305	Tin Silver Copper	
SN100C	Tin Copper Germanium Nickel	
SnPb	Tin Lead	
SM	Surface Mount	
Ta	Time to buoyancy	sec
Tb	Time to cross zero axis	sec
TFmax	Time to reach maximum force	sec
T <sub>s</sub>	Solder Temperature	°C
WEEE	Waste Electrical and Electronic Equipment	
WS	Water Soluble	
V	Volume	mm <sup>3</sup>

## Chapter 1 Introduction

The solderability of a component's metallic termination and a printed circuit board's (PCB) metallised pad is a critical parameter in any soldering operation. It represents the likelihood of that termination forming a good alloy with the solder and a high quality-solder joint. [1] The most common electronic terminations are component leads and terminations, metallic pads on PCB's used for surface mount components (SM), and Plated Through Holes (PTH's) for pin-in-paste or wave soldered components. Unless these offer a reliably consistent level of solderability, soldering defect rates will be high, along with rework and scrap costs. Since the early 1990's there has been a constant strive to attain lower and lower defect PPM (Parts per Million) figures using quality tools such as Six-Sigma. [2] From this, manufacturing companies are forced to examine each and every aspect of the modern manufacturing process, in a move towards the pinnacle target of zero PPM.

An increasing worldwide demand for portable consumer electronics drives development of smaller, faster and more powerful electronic devices. Components in these devices continue to become physically smaller, more precise, and more robust. Often, failures of these devices appear as a result of failure of the package (i.e. when a mobile phone is dropped) and specifically come as a result of failure of the solder joint. With the use of these smaller fine pitch components, the impact of poor solderability increases as well as the financial cost of rework or scrap to the manufacturing company. Although components are generally assembled from parts of known 'good' solderability, there is no way of guaranteeing this without a reliable and repeatable solderability test. [3]

Two tests available to assess the soldering ability of a component termination are the Dip & Look and Wetting Balance tests. Most component suppliers use a Dip & Look solderability test to verify the soldering ability of the component. The subjective nature of the Dip & Look test is always a concern for any manufacturing company who solder millions of components on a daily basis because results are determined by an operator visually inspecting components and deciding on a result, namely, pass or fail. [4]

The most effective quantitative method for measuring, testing and recording solderability is the Wetting Balance test. In essence, a Wetting Balance test exploits the fact that if a metallic body is dipped into a bath of molten solder, the weight and speed with which the solder meniscus climbs upwards on the body's immersed surface indicates how well the solder wets to it and thus its solderability. In simple terms, the greater the solderability the higher the meniscus will climb and the higher the force. Some suppliers who use a Wetting



Balance test machine do not use it as a means to determine the solderability but as a qualification purpose if the termination plating thickness has changed on the component. [5]

In this document the Dip & Look test will be assessed in terms of its accuracy and repeatability when testing components. To provide a reliable and repeatable test to assess the solderability of millions of components, the requirement is to have a controlled solution in place that will provide the result automatically. With the current manual method of Dip & Look used throughout many industries, the risk of poor soldering components passing the test is extremely high.

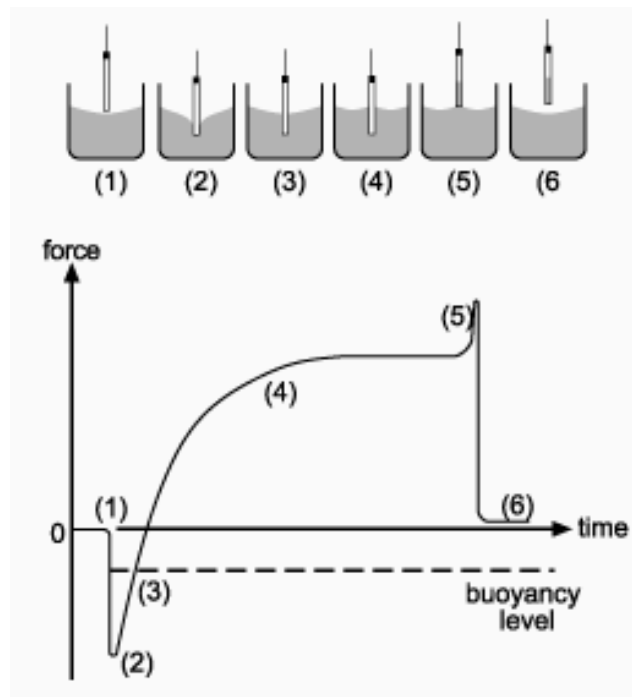
The Wetting Balance test is capable of providing such a robust method of assessing the solderability of components once the different settings within all the international standards are optimised. There are various international standards with conflicting settings for each of the main variables, solder temperature, immersion speed, immersion depth, and dwell time. Table 1.1 summarises the variation between each standard for the aforementioned variables.

**Table 1.1 Range of Settings from International Standards**

International Standard	SnPb / Pb-Free	Solder Temperature	Immersion Speed	Immersion Depth	Dwell Time
J-STD-002C	SnPb	245 $\pm$ 5°C	1mm/sec - 5 mm/sec	0.1mm	5 $\pm$ 0.5 sec
J-STD-002C	Pb-Free	255 $\pm$ 5°C	1mm/sec - 5 mm/sec	0.1mm	5 $\pm$ 0.5 sec
JESD-22-B102D	SnPb	245 $\pm$ 5°C	25.4mm/sec $\pm$ 6.4mm/sec	Fully Immersed	5 $\pm$ 0.5 sec
JESD-22-B102D	Pb-Free	255 $\pm$ 5°C	25.4mm/sec $\pm$ 6.4mm/sec	Fully Immersed	5 $\pm$ 0.5 sec
IEC68-2-69	SnPb	235 $\pm$ 3°C	1mm/sec - 5 mm/sec	1mm	5 sec
IEC68-2-54	SnPb	235 $\pm$ 3°C	4mm/sec - 21mm/sec	2mm - 5mm	0 - 10sec
IEC68-2-54	Pb-Free	245 $\pm$ 3°C	4mm/sec - 21mm/sec	2mm - 5mm	0 - 10sec

The variation of settings between each standard can have an affect on the result depending on the international standard used. The range of solder temperature values vary from 232°C to 250°C for a leaded process and 250°C to 260°C for a lead-free process. Similarly for immersion speed there is variation from 1mm/sec to 31.8mm/sec and also for immersion depth a range of values from 0.1mm to fully immersed test specimens. These variations can drastically affect the results depending on what end of the range are used.

Figure 1.1 illustrates the key aspects of the Wetting Balance graph. The start of the test is referenced at Point 1 when the test specimen is located over the solder bath. As the test specimen is immersed to a predefined depth into the solder bath of the Wetting Balance machine the solder is repelled away from the test specimen, Point 2. With immersion speed variation between 1mm/sec to 31.8mm/sec and immersion depth variation from 0.1mm to a fully immersed test specimen lead, the impact between the test specimen and the repelling of solder in the bath can be very significant and influence the result at Point 3 and Point 4. The buoyancy level ( $T_a$ ) is reached at Point 3 and the solder starts to wet to the test specimen and crosses the zero line ( $T_b$ ) until it reaches its maximum height (force) at Point 4 which is  $F_{max}$ . After two and five seconds of testing the forces are recorded for  $F_1$  and  $F_2$  respectively. At Points 5 and 6 the test specimen is automatically removed and the test is complete. [6]



**Figure 1.1 Wetting Balance curve with stages of testing 1 – 6 [6]**

There are specification requirements stated within the various international standards to be achieved by all test specimens when using the Wetting Balance method. The time to buoyancy ( $T_a$ ) must be reached within 0.6 seconds and the time to cross the zero line ( $T_b$ ) must be reached within one second. For the force values, force after two seconds ( $F_1$ ) and force after five seconds ( $F_2$ ), the specification is set at “no less than 50% of  $F_{max}$ ” and “no less than 90% of  $F_1$ ” respectively. [7]

Although literature covers a wide variety of information on soldering and various test methods such as the Dip & Look and Wetting Balance tests, there currently is no analysis performed on the impact of varying the parameters of the Wetting Balance machine and

understanding how these may influence the results. Even when results are currently determined from the Wetting Balance machine, there is no means of evaluating if the result achieved is 'good' or 'bad' other than the specifications in the international standards that only specify target values for the time variants,  $T_a < 0.6$  second and  $T_b < 1$  second. As mentioned earlier for the force responses  $F_1$  and  $F_2$ , specification limits of 'no less than 50% of  $F_{max}$ ' and 'no less than 90% of  $F_1$ ' respectively are stated but this project will highlight the insignificance of these limits.

This research will assess the impact of varying the aforementioned test variables (solder temperature, immersion speed, immersion depth, and dwell time) on each of the responses ( $T_a$ ,  $T_b$ ,  $F_{max}$ ,  $TF_{max}$ ,  $F_1$  and  $F_2$ ) using the Wetting Balance test, by testing at different ends of the variable specifications and determining what impact this can have on the results for each response.

Another key objective of this thesis is to develop mathematical model equations that precisely predict values for each of the six responses  $T_a$ ,  $T_b$ ,  $F_{max}$ ,  $TF_{max}$ ,  $F_1$  and  $F_2$  when assessing the soldering ability of a test specimen. These equations will afford the user comprehensive predicted values that can be used as a guide to compare with the actual values obtained by using the Wetting Balance machine. In the event this research ascertains the weakness of the various specification standards it will be required to update all solderability test standards using a Wetting Balance machine with these new specifications.

With regards to the globally used principal method for assessing solderability, Dip & Look test, no comprehensive research is available to show if this test method is sufficiently reliable for component suppliers to use at their means of checking for solderability. A complete evaluation of this test will be compiled to assess its repeatability and reliability. If there is sufficient evidence to show the inconsistency of this test, then it will be recommended that the Dip & Look test be removed as a means for assessing solderability. Now that the current problems have been outlined, the next chapter will focus on the available literature and research that has already been accumulated in the area of solder composition, solderability and the factors affecting it, legislation that limits the choice of solder alloys, and finally the Dip & Look and Wetting Balance tests and how the current methods are undependable. Throughout the literature review it will show how this new research can set new reliable and repeatable criteria that can be used by all users of the Wetting Balance test and thus provide a high level of confidence in screening out poor soldering components prior to use in series production.

## Chapter 2 Literature Review

### 2.0 Introduction

When solderability problems take place within a manufacturing company who are targeting lower and lower PPM defects, the biggest challenge is to determine the root cause as early as possible to minimise costs. [8] Given the fact that there may be several different types of equipment in each production line, this adds to the difficulty of trying to source the root cause. Examples of some of the main differences are listed below, all of which are extra variables in the investigation.

- Tin-lead (SnPb) soldering process versus lead-free (Pb-free) soldering production lines.
- Production lines with 3D post-solder paste inspection (SPI) versus a line without 3D post-solder paste inspection.
- Production lines with Nitrogen reflow soldering versus a line without Nitrogen reflow soldering.
- Production lines with Automated Optical Inspection (AOI) versus a line without Automated Optical Inspection.
- Stencil thicknesses differ from a 125-micron stencil to a 175-micron stencil thus varying volume of solder paste under the component termination.
- Solder paste applications – rheopump versus squeegees.

Millions of euros are invested to detect and improve soldering defects. [9] 3D Solder Paste Inspection (SPI) and Automated Optical Inspection (AOI) are two machines used on many SMT (Surface Mount Technology) lines to detect any possible defects. SPI machines measure the volume of solder paste on the pads of a PCB to ensure the correct volume of paste is present and is sufficient to help form a good solder-joint. AOI machines inspect the solder joint quality of each component on the PCB. Nitrogen is used in reflow soldering to reduce the oxygen levels within the reflow oven chamber, preventing the solder pads and component terminations from further oxidising during the soldering process. Many manufacturing companies have seen the benefits of Nitrogen in reducing the soldering defects but the costs for such a process is expensive. [10]

When solder defects are detected using the aforementioned machines, assessing the components soldering ability is a key investigation to be carried out. Solderability testing pertains to the process of evaluating the solderability of component terminations as well as printed circuit board pads. [10] There are many industry standards for performing solderability testing. Some of these include the following:

- 1) IPC/JEDEC J-STD-002 Solderability Tests for Component Leads, Terminations, Lugs, Terminals and Wires.
- 2) IPC/JEDEC J-STD-003 Solderability Tests for Printed Boards.
- 3) IEC-60068-2-54 Solderability testing of electronic components by the Wetting Balance Method.
- 4) IEC-60068-2-69 Solderability testing of electronic components for surface mount devices by the Wetting Balance Method.
- 5) JESD22-B102 Solderability test for leaded and leadless components

There are conflicting parameter settings between each of the aforementioned tests above and these were detailed in Table 1.1. For example, the solder temperature values range from 232°C to 250°C for a leaded process and from 250°C to 260°C for a lead-free process as well as immersion speed variations from 1mm/sec to 31.8mm/sec and immersion depths from 0.1mm to fully immersed component leads. With these variations there is a high potential for discrepancy within the results depending on the combination of settings used. This literature review will research solder and how it has evolved since its first use thousands of years ago and also the theory for soldering. In recent years there has been new legislations passed within the European Union (EU) that have banned the use of lead (Pb), one of the main metals used to form a solder joint in modern times, which had a huge impact on the predominant alloy tin-lead (SnPb).

Various companies as a result of these directives developed new metal alloy combinations. From these new alloys, two are used for this project along with tin/lead (SnPb), namely SAC305 (Tin, Silver, Copper) and SN100C (Tin, Copper, Germanium, Nickel). These three alloys are used to assess the robustness of the two main solderability tests, Dip & Look and Wetting Balance tests. All testing will be conducted using a MUST II Wetting Balance and for the benefit of reducing any possible variation of solderability between component leads, 0.9mm diameter copper wires were used as the test specimens for the Wetting Balance analysis.

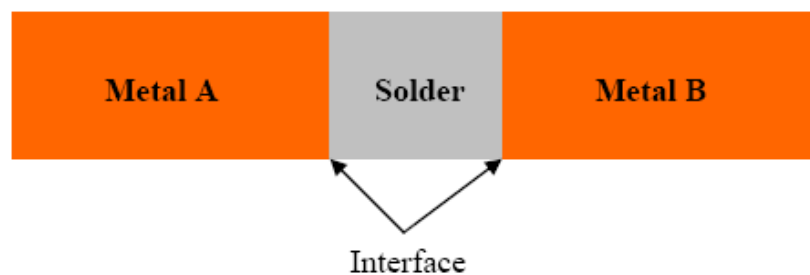
This research will try and understand the impact of using varying parameters settings and how these settings can influence the result when testing components of known solderability problems using Design of Experiments (DoE).

## **2.1 Solder – An Overview**

Solders have been in use dating back to about 4000BC and have been a very important part of life through the Bronze and Iron Ages up to the so-called ‘Silicon Age’. The Greeks sealed bronze-based water and air pumps with tin-lead alloys and the Romans used tin-lead

solders extensively in the construction of aqueducts and to close the seams of lead water pipes. Early in the twentieth century, soldering was introduced to the electronics industry as a reliable method of connecting copper wires. Today in electronics, soldering continues to be the predominant means to attach electronic components to printed circuit boards, PCB's. [11]

Soldering can be described as two metals bonded by solder. When two metal parts are joined by solder, a metallic continuity is established as a result of the two interfaces where the solder is bonded to both metallic parts. Figure 2.1 shows the metallic continuity from metal A to metal B where a metallurgical bond is formed by the solder. The solder serves both as a bond maker and a link in the metal continuity. [12]



**Figure 2.1 Two metals bonded by solder [12]**

A key requirement to form this metal continuity is the solderability of both metal surfaces. It is required to have both surfaces free from any oxides so that the metallurgical bond can be formed. Any oxides present may prevent the solder joint forming or may result in a degraded solder joint and poor solderability. [12]

There are three aspects to solderability: 1) Thermal demand, 2) Wettability, 3) Resistance to soldering heat. The thermal characteristics of the component to be soldered must enable the solder joint areas to be heated to the desired temperature for soldering within the time available for the soldering operation. The solderable surfaces must allow the molten solder to wet and spread during the available time without subsequent de-wetting. The soldering heat and induced thermal stresses associated with it must not affect the functioning of the components beyond a specified limit. The above three requirements can be engineered to fit a particular application by a suitable choice of component materials. The most restraining of these three parameters during soldering is the wettability of the component. [13]

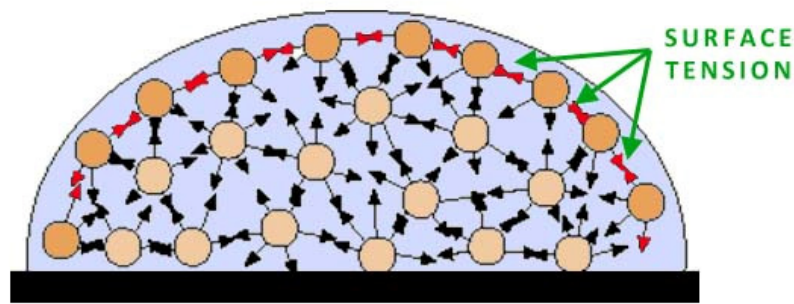
### **2.1.1 Wettability**

From researching various literatures for wettability there are two important characteristics to be considered:

- The degree of wetting – how far the solder spreads and wets over the area to be soldered. This is an equilibrium situation governed by the laws of thermodynamics and dependent on the surface and interfacial tensions involved in the solder and component front. [13]
- The speed of wetting – how fast the solder wets and spreads over the area to be soldered. This is governed by the thermal demand of the component, the ability of the heat source to supply that heat and the efficiency of the flux. [13]

### 2.1.1.1 Degree of Wetting - Surface Tension

The ease or restriction with which the solder wets is determined by the surface tension of the surface to which it is supposed to adhere to. Surface tension ( $\gamma$ ) can be easily defined if one imagines a free droplet of molten solder, held in free space, the droplet will form into a globule shape, just as a free droplet of water will form into a spherical shape as shown in Figure 2.2. [14]



**Figure 2.2 Droplet of water showing Surface Tension [14]**

The drop is held in this shape by the surface tension force of the water droplet. Inside the droplet atoms surround atoms equally, and the net force on them is zero. At the surface there is an imbalance in the inner-atomic attraction forces, as the surface atoms experience a net force into the body of the droplet. The complete system tries to adopt a shape that has the minimum free energy, which means the minimum surface to volume ratio. This situation is achieved when the molten solder forms into a sphere. [14]

The surface tension is the magnitude  $F$  of the force exerted parallel to the surface of a liquid divided by the length  $L$  of the line over which the force acts:

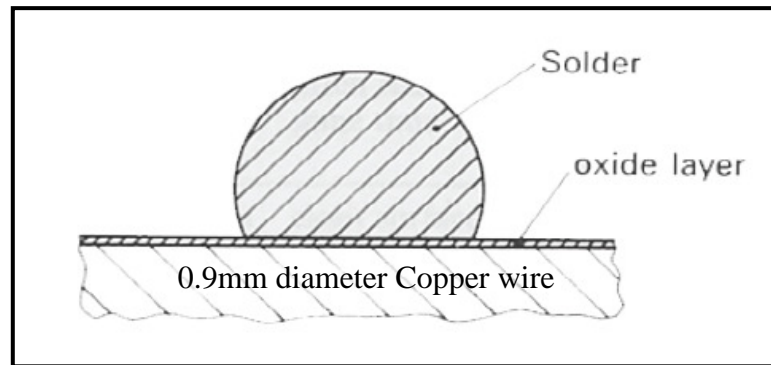
$$\gamma = F / L \dots \dots \dots \text{Eq-2.1 [15]}$$

The unit of surface tension is Newton per meter (N/m). [15] Some typical surface tensions of common liquids are shown in Table 2.1. Taking the example of water, it can be seen that an increase in temperature will result in a decrease of surface tension.

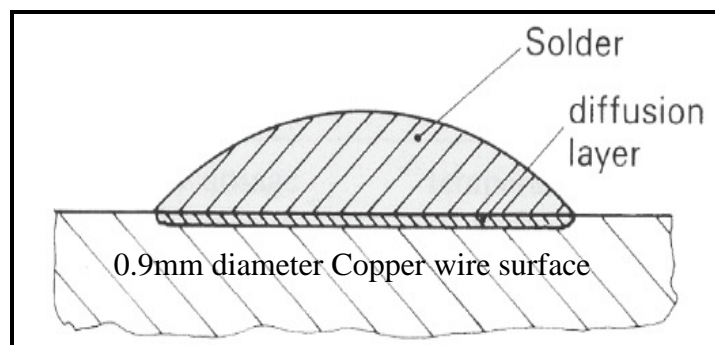
**Table 2.1 Typical surface tensions of common liquids [15]**

Liquid	Surface Tension (N/m)
Benzene 20°C	0.029
Glycerine 20°C	0.063
Mercury 20°C	0.47
Water 20°C (100°C)	0.073 (0.059)

If a molten sphere of solder is placed onto a heated, oxidised copper wire, it will show that the shape of the sphere is depressed by gravity, to form a sessile drop, as shown in Figure 2.3. [16]

**Figure 2.3 Sessile drop of solder on oxidised copper wire surface [16]**

Similarly for a component through-hole lead that has oxidised, the solder wetting is restricted due to this layer of oxidation and will therefore result in poor wettability. If a suitable flux is now added to the sessile drop, on the oxidised copper wire, the oxide layer will be removed from the copper wire and the solder, and the tin in the solder will react with the copper wire to form an intermetallic layer (diffusion layer as shown in Figure 2.4), allowing the solder to spread as shown in Figure 2.4. The breakdown of the oxide film is vital to achieve true wetting in any system. [16] In order to prove this theory, components will be aged using accelerated aging and tested using the Dip & Look and Wetting Balance tests to see how it will affect the results in this project.

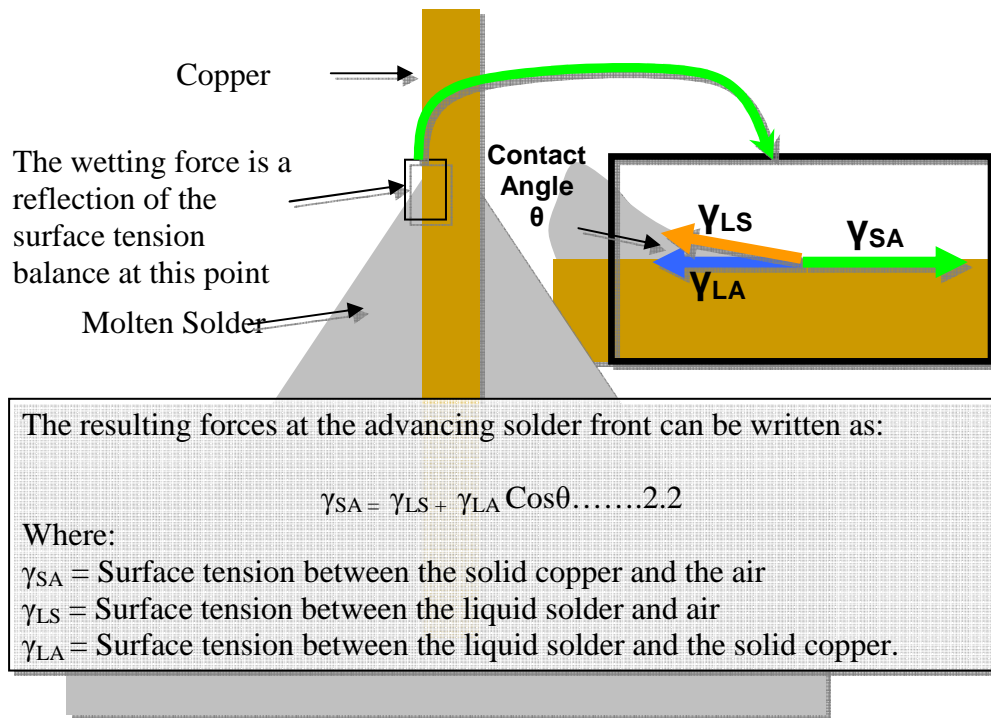
**Figure 2.4 Sessile drop of solder with flux on copper wire surface [16]**



The final shape of the spreading solder will depend on the surface tension forces acting at the interfaces. Solid and solid-liquid interfaces also exert a surface tension force, and all try to reduce their surface areas to a minimum, to attain a minimum free energy. The result is that equilibrium is set up as shown in Figure 2.5, where the net force at the advancing solder front is zero. [16] Young's Equation is used to calculate the level of wetting achieved on a surface using the Contact Angle of the solder. [17]

### 2.1.1.2 Young's Equation

Figure 2.5 shows the forces acting at the advancing solder front of a copper wire immersed in solder.



**Figure 2.5 Copper wire in molten solder [17]**

The surface tension of the solder copper in air is balanced by the surface tension between the liquid solder and the air, and the liquid solder and the solid copper. [17]

Equation 2.2 is known as Young's Equation, and it can be seen that the Contact Angle,  $\theta$ , can be used as a measure of the degree of spreading obtained. The smaller the Contact Angle, the greater the spreading, and the better the wetting obtained. Contact Angles are used as a measure of the wetting interaction between a liquid (molten solder) and a solid (copper wire) and are extremely sensitive to contamination. By re-arranging Young's Equation 2.2 we get:

$$\cos\theta = \gamma_{SA} - \gamma_{LS} / \gamma_{LA} \dots\dots \text{Eq-2.3 [16]}$$

For wetting to occur it is required to have the Contact Angle,  $\theta$ , to be less than  $90^\circ$ . That is a requirement to have  $\cos\theta$  between 0 and 1 and preferably to be as close to 1 as possible. If  $\cos\theta$  is less than 0 then the Contact Angle will be greater than  $90^\circ$ .

From Equation 2.2, in order for wetting to occur,  $\gamma_{LS}$  is required to be low,  $\gamma_{SA}$  to be high and  $\gamma_{LA}$  to be high. The surface tension between the solid and the air,  $\gamma_{SA}$ , will be high when the solid is free from oxides, sulphides, chlorides, hydrocarbons and other surface contaminants, which will all reduce the surface tension. [16]

Young's Equation is important for this research because it explains theoretically the method of solder wetting to a surface. Even though the Wetting Balance machine does not measure the Contact Angle or give a result  $\theta$ , the Contact Angle can be determined from the wetting force measured by the Wetting Balance machine. This will be discussed later in Section 2.4.4.

### **2.1.2 Solderability**

Solderability has many definitions. As defined by IPC: Components - IPC J-STD002C:

*...to verify that the solderability of component leads, terminations and printed wiring boards, meets the requirements established by standards and that subsequent storage has no adverse effect on the ability to solder*  
*...to determine that the dissolution of metallisation on terminations will remain intact throughout the assembly soldering process*  
*...The determination of solderability can be made at the time of manufacture, at receipt of the boards or components by the user, or just before assembly and soldering.* [7]

#### **2.1.2.1 What Determines Solderability?**

The difficulty with which a metal can be soldered is determined by the ease with which a metallurgical bond can be formed between the printed circuit board, the tin in the solder, and the component lead. To form a bond between these, all three must come into molecular contact and form an intermetallic layer. The key factors that determine solderability are:

- Printed Circuit Board and Component Termination
- Solder Composition
- Ageing [17]

##### **2.1.2.1.1 Printed Circuit Board (PCB) and Component Termination**

It is well known that some metals are much easier to solder than others. Copper, for example, is much easier to solder than nickel, which in turn is easier to solder than Aluminium. A common type of plating on PCB pads is Nickel-Gold (NiAu). Gold is commonly used as a barrier layer to prevent oxidation of the Nickel layer during the

different processes. The thickness of the Nickel is typically a nominal of 5 $\mu\text{m}$  and the thickness of the over-layer of Gold is usually 0.05 $\mu\text{m}$  to 0.1 $\mu\text{m}$ . [17]

In order to form a bond the PCB and the component termination must be free from contamination such as oxides, chlorides and sulphides. A flux is used in the soldering process is to remove contamination from the solder, PCB and component termination, and protect the surfaces until the clean PCB, termination and solder can be brought into contact during soldering. [17]

The stability of the contamination compound formed with the PCB and component termination will obviously have a severe effect on the ease with which a PCB and component termination will solder. The more stable the contamination compound formed, the more difficult it will be for the flux to remove this contamination. [18]

The extent of wetting will also be affected by the physical condition of the surface, in particular the surface roughness. Although there are conflicting reports as to the effect of surface roughness, it is generally accepted that roughening a surface will reduce the extent of spreading by an advancing solder front. [18]

#### **2.1.2.1.2 Solder Composition**

The composition of the solder alloy will affect the surface tension of the liquid solder since relatively small concentrations of impurities in the solder can have a marked effect on the wetting properties of the solder. For this project three alloys are used, namely SnPb (tin-lead) for the leaded process, SAC305 (Tin-Silver-Copper) and SN100C (Tin-Copper-Nickel-Germanium) for the lead-free process. From Young's Equation, as discussed in Section 2.1.3, it can be seen that in order to produce a low Contact Angle, a low surface tension between the liquid solder and the PCB is required, which occurs when a metallurgical bond is formed. The surface tension of a liquid is determined only by the surface composition, and not by the composition of the bulk of the liquid. Contaminants with low surface tensions will tend to migrate very rapidly to the solder surface, reducing the surface tension at the surface. [19]

On the Wetting Balance machine it was evident from all testing that was conducted for this project; there was a high tendency for contaminants to form on the surface of the solder in the bath. After each test run, there was a requirement to remove this layer of contaminant on top of the solder before testing a component lead. As this research has shown, the contaminant can affect the surface tension and therefore affect the results from the Wetting Balance test.

### 2.1.2.1.3 Ageing

Ageing is the natural process by which the solderability of a component or PCB will decrease with time due to the accumulation of oxidation. The majority of component terminations and PCB finishes are formed from a base material over which a solderable coating is applied to retain its solderability. It is common practice to place a barrier layer over the base metal, before applying the solder coating, particularly if the base metal has a high solubility in solder. [20]

Exposed surfaces such as copper rapidly oxidise in air at room temperature, and although fluxes are currently available that will remove these oxides, they are usually regarded as too aggressive for normal production line soldering. [20]

The vast majority of electronic component terminations are coated with tin or (prior to lead-free legislation) tin-lead, and so most of the intermetallic layers contain tin - diffusion layer as shown in Figure 2.4 and will be discussed in detail later in this chapter. [21]

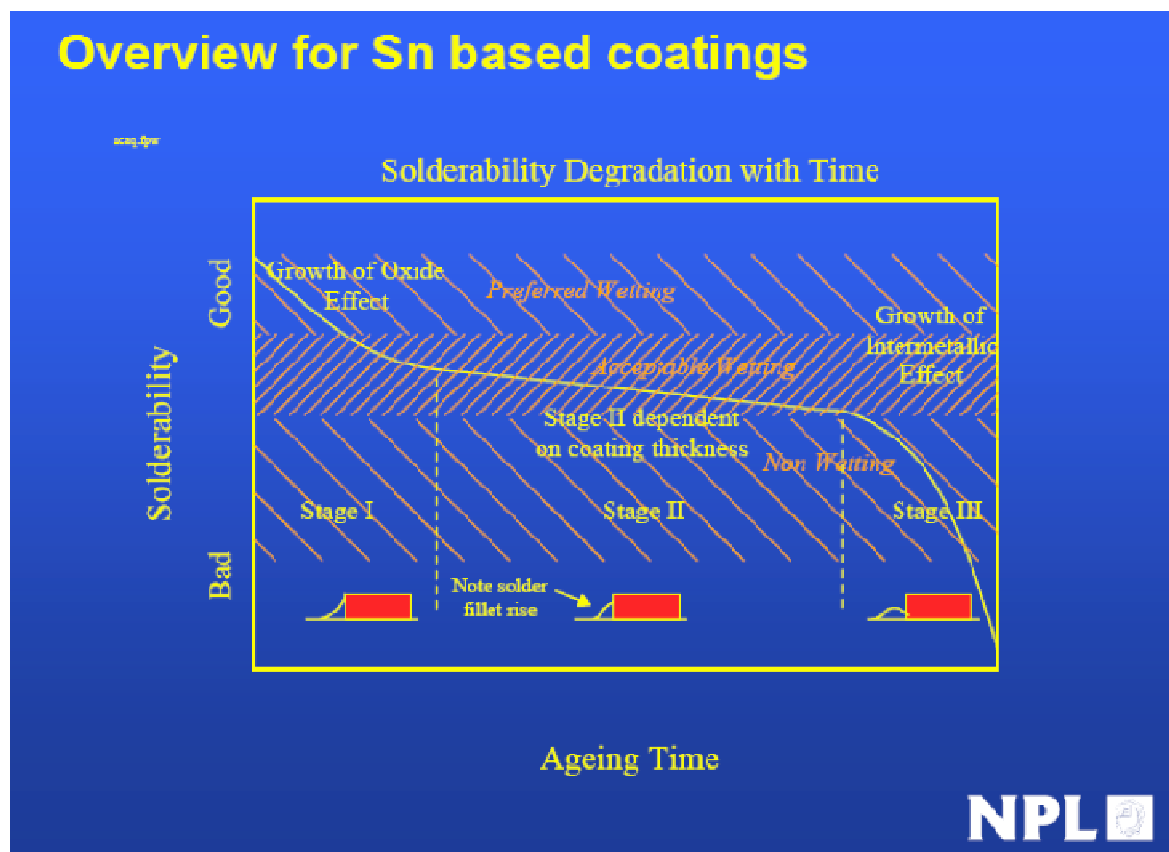


Figure 2.6 Wetting time of a solderable PCB surface against ageing time [21]

While the solder is molten, the intermetallic layer is continually forming and being dissolved. Figure 2.6 shows three distinct phases. Firstly the wetting time starts to increase as the solderability is reduced by the formation of oxides or corrosion products on the solder surface. Then there is a phase where no further deterioration occurs as the solder

oxide layer protects the solder from further oxidation, by reducing the diffusion through the oxide layer and a chemical passivation of the surface. In the third phase the intermetallic layer has grown through to the surface of the solder coating, and the wetting time again begins to increase. [21] For the Dip & Look test and Wetting Balance tests evaluation in this project, ageing will be considered to understand its affect on the results.

When components are purchased they can be tested to ensure that their initial solderability is acceptable. Unless very strict just-in-time practices are used, it is always possible that some components will be stored for excessively long periods before they are used or the supplier before delivery may have stored them. [22]

Clearly it is impossible to produce an ageing method that will provide the same ageing mechanism as natural ageing. The international solderability specifications include a number of methods to accelerate the ageing process, although the exact mechanism could never be the same. [21]

- IPC-J-STD-002C states a Steam Conditioning for 8 hours +/- 15 minutes
- JESD22-B102 specified the use of Dry bake in air at 150°C for 15 hours +/- 15 minutes – this is an alternative to steam conditioning.

For IEC-60068-2-54 “Solderability testing of electronic components by the Wetting Balance Method” and IEC-60068-2-69 “Solderability testing of electronic components for surface mount devices by the Wetting Balance method” no preconditioning is specified. It does however state to use the component specification preconditioning which should be stated in the material safety data sheet (MSDS). [21]

#### **2.1.2.2 The Advantages of Good Solderability**

- Improved Joint Strength and Reliability

The use of components with good solderability improves the extent or spread of wetting that occurs during soldering, and so produces a much stronger, more reliable solder connection. A solder joint with a well defined solder fillet will have a much longer lifetime and be better able to withstand thermal cycling in use. [23]

- Stable Electrical Contact

A component with good solderability will form a strong uniform bond, giving stable and reliable electrical contact. [23]

- Lower Soldering Temperatures

The soldering rate is proportional to the soldering temperature. By using components with good solderability the soldering temperature can be kept low, which prevents damage to sensitive components and also prevents the use of rosin activated fluxes. [23]

- Short Soldering Times

Good components only need to be at the soldering temperature for a short period, again reducing the risk of damaging heat sensitive components. Short soldering times will also reduce the thickness of the intermetallic phase formed during the soldering process. [23]

- Use of Low Activity Fluxes

Components and printed wiring boards with good solderability can be soldered with mildly activated fluxes. This results in a reduced risk of leaving corrosive materials on the board, which could affect reliability. It is also much easier to remove a weak flux residue than a strong flux residue from a printed wiring board after soldering. Again this reduces the risk of leaving potentially harmful flux residues on the printed wiring board. [23]

- Uniform Soldering Times

The use of components with good solderability ensures uniform soldering times, particularly important on multi-leaded devices and chip devices during reflow soldering. Non-uniform soldering can result in the component being misarranged during the soldering process, or in the case of chip components, being pulled off the pads or even standing on one end (tomb-stoning). [23]

- Cost Effectiveness

This is always the most difficult benefit to justify, but it is much easier and less costly to prevent components with poor solderability reaching the production line than to have to find and rectify a faulty solder joint after production. The repaired joint will never be as good as a joint made correctly the first time. [23]

### **2.1.2.3 Summary of Key Research Points**

- The solderability of a component lead or termination and the PCB through-hole is a key requirement in forming a solder joint. The main requirements of solderability are;
  - Thermal demand of the component to ensure it is capable of soldering within the time available for the soldering operation.
  - Wettability of the surfaces to be soldered which is determined by the surface tension. To quantify the amount of wetting, Young's Equation is used in conjunction with the measure of Contact Angle  $\theta$ .
- The Wetting Balance machine does not calculate the Contact Angle  $\theta$  but one can calculate this mathematically using the Wetting Force formula and the  $F_{max}$  result. A Contact Angle,  $\cos\theta$ , between 0 and 1 is preferable to ensure wetting.

- To achieve optimum solderability it is preferred to have the PCB surface and component termination free from any oxides. When conducting solderability testing in this project all test specimens will be cleaned using a flux directly before the actual test to minimise any re-oxidisation.
- Another key requirement to ensure good solderability is the age of components and how well they have been stored before use in the production line. Figure 2.6 highlighted that the solderability reduced over time. An accelerated ageing process will be considered in this project when assessing the Dip & Look and Wetting Balance tests.

## **2.2 Fundamental of Soldering**

As mentioned earlier, soldering has been in use for centuries and the evolution throughout the years has continued and even in today's fast moving industry it continues to gather pace. The most commonly used solder is an alloy of tin and lead. Due to the poisonous qualities of lead and various legislations, lead-free solders are in the process of substituting tin lead solder. During the last couple of year's the electronics industry has focused remarkably on the use of tin-silver-copper (SAC) solder family as a lead-free solder. The solder price is an essential factor in this decision and precious metals such as silver increase the solder price. That is why alternative lead-free solders with very low silver content or solders without silver (SN100C) are considered for use in wave soldering. The electronics industry requires solders to have the following properties:

- Compatibility with copper with respect to alloying behaviour and melting temperatures.
- Good electrical conductivity.
- Workability to ensure low-cost, reliable solder joints. [24]

Engineers have now developed guidelines to govern the design of solder joints used in various applications to ensure the required levels of strength. The materials, such as the components, and processes involved in soldering are now established in the engineering practice. [24] Soldering technology depends on certain fundamental parameters and the issues associated with each. These are:

- Solder Alloy
- Component material
- Flux [25]

### **2.2.1 Solder Alloys**

A solder is an alloy with specific properties, such as melting point and wetting capability, which make it suitable for use as a solder. Almost the entire electronics manufacturing process consisted of the tin-lead (SnPb) alloy, with or without the addition of other elements. That was until the environmental and health aspects of the lead raised concerns and therefore came legislations, Waste Electrical and Electronic Equipment (WEEE), Restriction of Hazardous Substances (RoHS) and End of Life Vehicle (ELV) directives, which will be discussed later. As a result of these impacts, there have been studies to try and determine the best-suited alternative alloy without the use of lead. [25]

#### **2.2.1.1 Tin/Lead (SnPb) Alloy**

SnPb eutectic solder is still used in specified areas such as the military, aviation and health due to exemptions in legislations. It was used within the electronics industry for many years because of the following:

1. Good wettability with the aid of mildly active fluxes.
2. No brittle intermetallic compound formations in solder.
3. Low melting point to permit the design of components that can endure the high temperatures associated with the soldering process. [26]

Tin is normally alloyed with lead to produce solders, with 60–63% by mass of tin being used in most electronic assemblies. The melting point of pure tin is 232°C and it is reduced by the additions of lead to a minimum of 183°C at the eutectic composition of 61.9% tin. This lower temperature is compatible with the thermal properties of electronic components. In addition, the cost of tin is by far greater than the cost of lead and consequently the use of the higher tin alloys are seldom used. If the tin content is too low, besides the melting point increasing, there is a general reduction in the wetting properties of the alloy. [27]

#### **2.2.1.2 Tin/Silver/Copper (SAC) Alloy**

The most common replacement alloy for the SnPb is the combination of tin/silver/copper otherwise known as SAC. Tin-silver-copper solders are a solder family, where silver content is typically between 3.0 to 4.0-weight percentage and copper content between 0.5 to 0.9-weight percentage. Different SAC alloys may be denoted by an annotation SACx1x2y, where the first two numbers x1 and x2 indicate the silver content and the third number ‘y’ represents the copper content. Tin is considered to be the replacement metal for lead because of its ability to wet and spread over a range of surfaces. There are many different percentage variations of this alloy namely:



- SAC305 – Sn96.5%, Ag3.0%, Cu0.5% - one of the alloys used in this project
- SAC405 – Sn95.0, Ag4.0%, Cu0.5% [28]

The varying percentage of each alloy is mainly down to the supplier of that particular alloy. When the melting temperature of each alloy is approached, the mechanical stability of the solder joint is degraded and the elevated temperature cycling produces more damage for SnPb solder (melting point 183°C) as compared to the higher melting point solders. [28] Copper is added to SnAg in order to slow copper dissolution, lower the melting temperature, and improve wettability, creep and thermal fatigue characteristics. Some companies such as Nokia have found the yield and reliability results, comparable or better than SnPb [29], but investigations carried out by a laboratory in Tokyo in 2007 [30] have determined this to be incorrect. This will be discussed in detail later in the chapter.

#### **2.2.1.3 Tin/Copper/Germanium/Nickel (SN100C) Alloy**

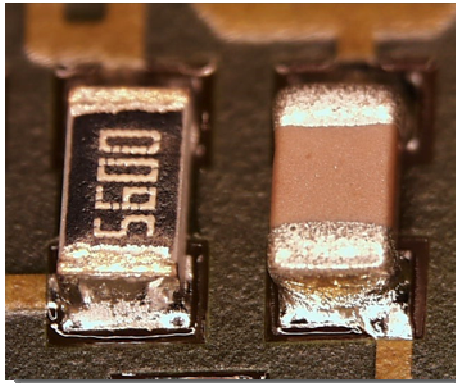
SN100C is a lead-free solder alloy, developed and patented by Nihon Superior Company Limited of Japan, that is composed of Tin (Sn), Copper (Cu), Nickel (Ni) and Germanium (Ge). Trace addition of Nickel and Germanium increases fluidity of solder, and it also improves wettability by reducing oxidation on the surface. [31]

Nickel brings the fluidity of SN100C up to about the level of SnPb by making SnCu behave like SnPb, i.e. as a eutectic. The Germanium migrates towards the surfaces where it acts as a sort of sacrificial antioxidant. A surface free of tin oxide is more mobile and so flows and drains more easily. [31] The reduction of oxidation on the solder surface was evident when conducting tests using the Wetting Balance machine. Even though, after each run the solder surface was cleaned using a spatula to remove a layer of oxides formed, the amount was smaller than that of SAC305 and SnPb alloys.

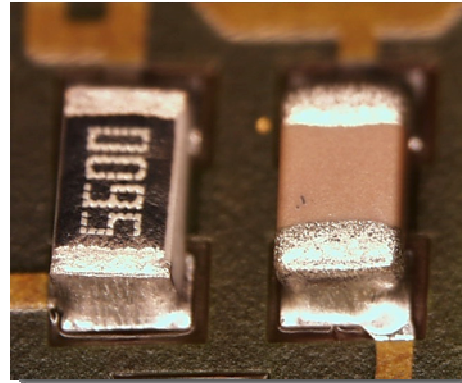
#### **2.2.1.4 SnPb vs. Pb-free – Physical Characteristics**

Visual inspection, whether manual or automated (AOI), which is used throughout the electronics manufacturing world to inspect for defects, is a very important aspect of the electronic assembly process. Accordingly, a set of visual inspection criteria has been identified by the IPC (Association Connecting Electronics Industries (formerly known as the Institute for Interconnecting and Packaging Electronic Circuits) and is generally practiced across the industry for both SnPb and lead-free solder joints. This inspection criterion is based on the standard IPC-A-610C. A visual appearance difference is evident from the standard SnPb compared to the new lead-free process. Figure 2.7 and 2.8 is an image taken from circuit board used on an automotive product using 0402 resistors and

capacitors. Figure 2.7 is soldered using a conventional SnPb alloy and Figure 2.8 is soldered using a SAC alloy. [32]



**Figure 2.7**  
**Resistor and Capacitor soldered**  
**with SnPb in air atmosphere [32]**



**Figure 2.8**  
**Resistor and Capacitor soldered**  
**with SAC in air atmosphere [32]**

Visually the difference between both is very obvious in that the SnPb joint is much brighter and cleaner than the SAC joint. In terms of solder joint strength comparison between SnPb and SAC305, both are very comparable and this will be discussed later in the chapter. From experience with working for an automotive electronics manufacturing company, the changeover from the SnPb process to the lead-free process brought with it some difficulties and challenges. [32]

The dull grainy joints from the typical lead-free process [Figure 2.8] proved to be a difficult decision for the operator / machine to make initially. Good lead-free solder joints were sometimes labelled as ‘bad-joints’ due to the inexperience of the operator but with sufficient training, a level of confidence was achieved. Similarly for the Dip & Look test the results are based on an operator making a decision for a good or bad result. This was one reason for evaluating the Dip & Look test and is discussed in details later in the project.

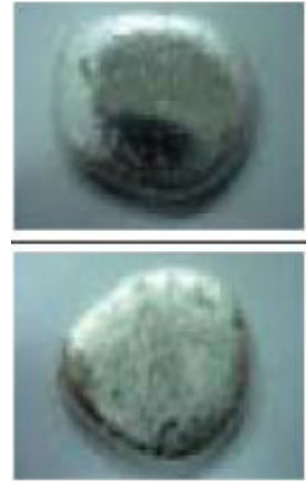
However, the appearance of the SN100C alloy is very different to that of most of lead-free alloys. As was stated earlier lead-free alloys tend to be dull grainy joints but the SN100C alloy gives a bright shiny joint similar to the replacement alloy SnPb. [33] Figures 2.9, 2.10 and 2.11 are 30mm diameter globules of solder and these show the visual similarity of the SN100C and SnPb alloys and the visual difference between SN100C and SAC305. [33]



**Figure 2.9 Sample of SN100C Alloy [32]**



**Figure 2.10 Sample of SnPb Alloy [32]**



**Figure 2.11 Sample of SAC305 Alloy [32]**

#### 2.2.1.5 SnPb vs. Pb-free – Reflow Soldering

Reflow soldering is a heating process that is used to solidify the solder paste to the component and Printed Circuit Board (PCB) metalised pad by reflow. Each alloy requires a different reflow profile due to the different heating requirements of the alloys. The first stage of reflow soldering is to dry the solder paste volatiles in order to prevent spattering and paste spreading. This is followed by a gradual heat up to just below the solder melting point, and soaks the solder at that temperature. This will make sure that all components to be soldered will reach the same temperature. The melting point is then followed where the solder wets to the components. The final stage is the cooling process that cools all components slowly in order to avoid any cracks due to thermal shock. [34] Table 2.1 shows the reflow soldering characteristics for all three alloys, SnPb, SAC305 and SN100C.

**Table 2.2 Reflow Characteristics – SnPb vs. SAC305 vs. SN100C [31] [35]**

	SnPb	SAC305	SN100C
<b>Peak Temperature (°C)</b>	210 – 225	235 – 255	235 – 245
<b>Melting Point (°C)</b>	183	217	227
<b>Time above liquidus (sec)</b>	45-75	40-70	60
<b>Solder Density (g/mm<sup>3</sup>)</b>	8.4	7.4	7.4
<b>Surface Tension (mN/mm)</b>	0.4	0.5	0.5

Figures 2.12 and 2.13 are typical reflow profiles used in industry for an SnPb, lead-free alloys (SAC and SN100C) respectively. A reflow profile is developed using the recommendations from the component and solder paste suppliers develops the reflow profile. [36]

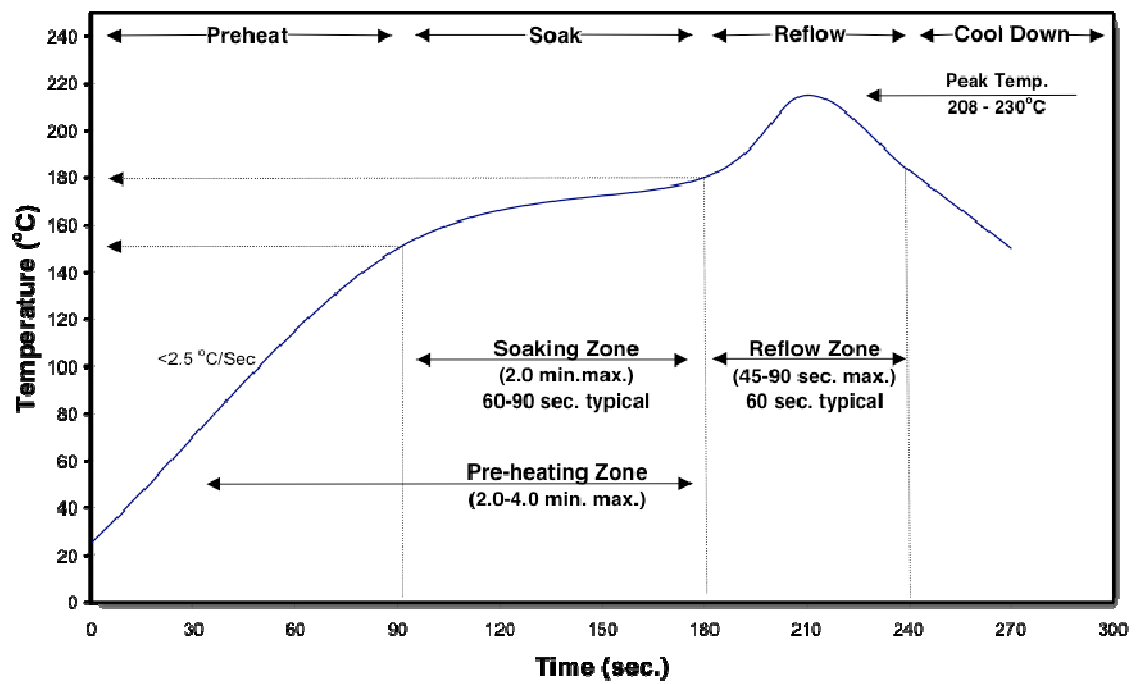


Figure 2.12 Reflow Profile for SnPb Alloy [36]

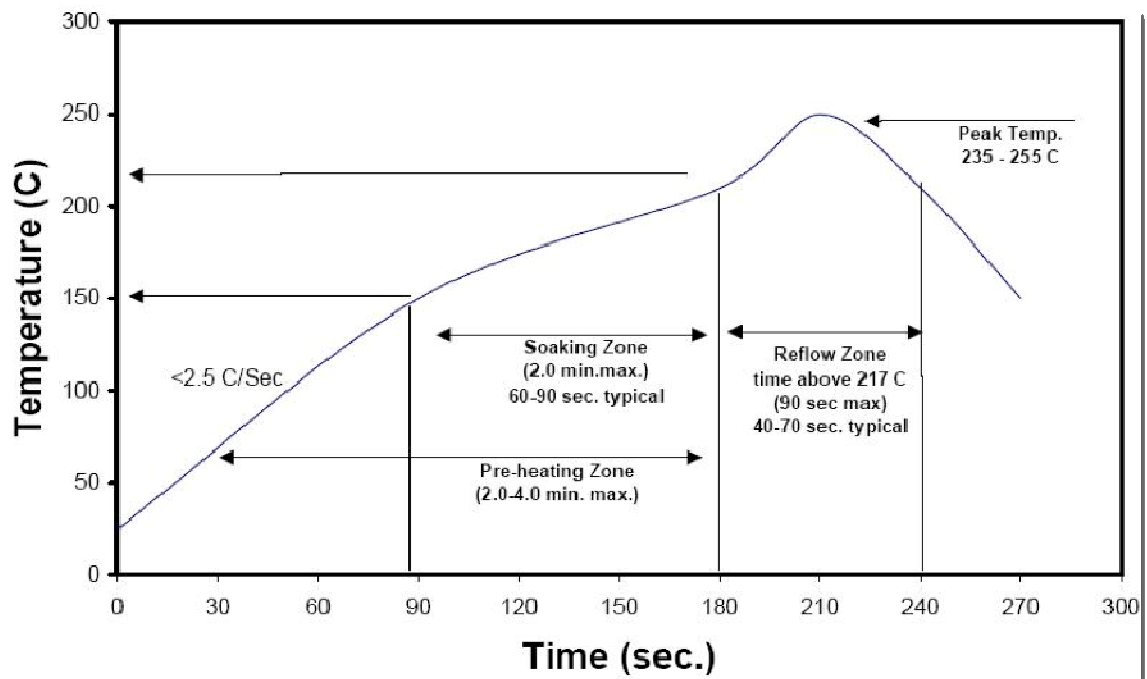


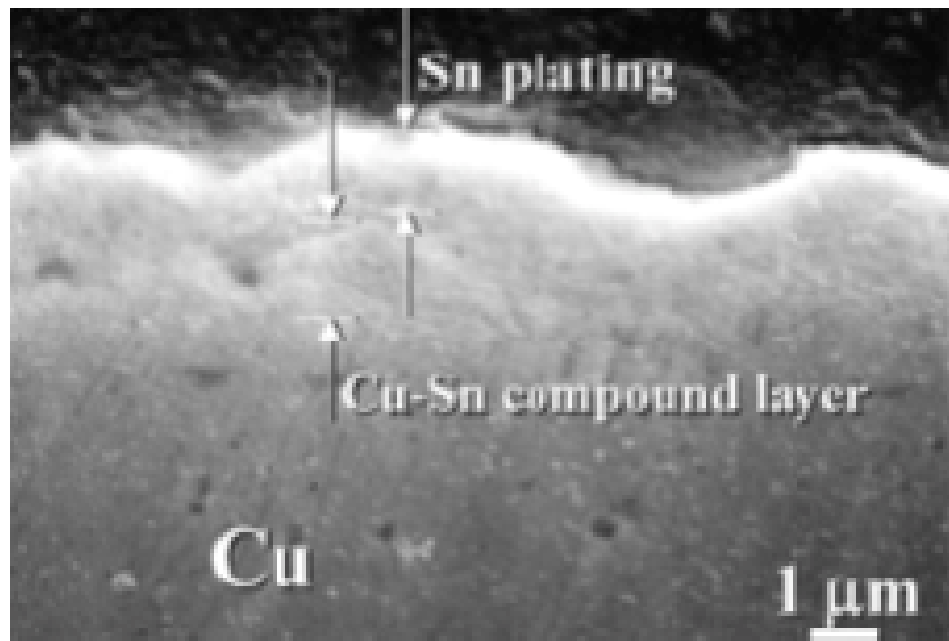
Figure 2.13 Reflow Profile for lead-free Alloys (SN100C and SAC305) [36]

The main concern when developing a new reflow profile for an electronic PCB is to ensure that all component sizes are soldered within the time allowed by the reflow oven. Larger components such as relays and Quad-Flat-Packs (QFP's) require a lot more heat than small chip capacitors and resistors. The reflow profile must ensure that the greater heat required for relays and QFP's must not have any negative effect on the chip capacitors and resistors. These elevated temperatures may affect the electrical characteristics thus hinder the functionality. [36]

### 2.2.1.6 SnPb vs. Pb-free – Thermal Fatigue Reliability

Since the introduction of the lead-free legislation a lot of focus has pointed in the direction of replacement alloys while keeping the strength and reliability of the solder joint to the forefront of the decision-making. In order to have a reliable solder joint, one must form inter-metallic layers between the solder material and the base metal. Inter-metallic layers are an indication of good metallurgical bonding but if it grows too thick, either during the soldering or subsequent solid stage aging, it can have a negative effect on the solder joint strength of a component. Within each inter-metallic layer, there are actually a number of different compounds formed by the solder materials and the base metal. These compounds are typically quite brittle and will adversely affect the integrity of the solder joint. As the joint is subject to stress, thermal cycles, vibration, or shock, the inter-metallic layers are usually where it starts to fail. Since the inter-metallic layers are inevitable, it is best to keep it as thin as possible. [37]

Figure 2.14 is an example of the intermetallic compound layer formed between two materials. Most studies have investigated the IMC growth during the solid stage but few have addressed the IMC formation in molten state with different alloys. The Ford Motor Company carried out such an experiment in 1996 [37].

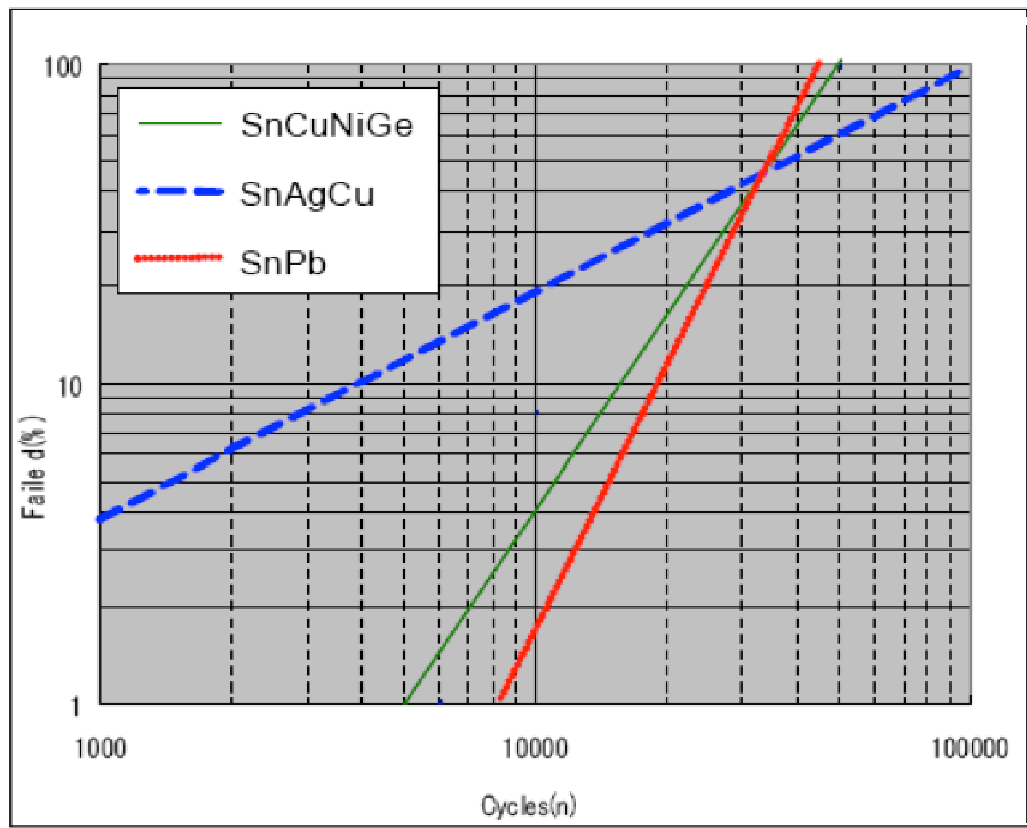


**Figure 2.14 Intermetallic Compound layer [38]**

The growth of the IMC  $\text{Cu}_6\text{Sn}_5$  between 100Sn, 96.5Sn3.5Ag and 63Sn37Pb solders on electroplated copper from the molten stage was examined. It was concluded that IMC with 96.5Sn3.5Ag and 100Sn solders grew less than  $1\mu\text{m}$  at 10 seconds to about 1.5 to  $2\mu\text{m}$  after 120 seconds at the lowest temperature and grew from  $1.5\mu\text{m}$  at 10 seconds to a thickness of about  $3\mu\text{m}$  after 120 seconds at the highest temperature. For 63Sn37Pb, the

IMC thickness started at about  $0.5\mu\text{m}$  at 10 seconds and grew to about  $0.7\mu\text{m}$  at the lowest temperature and grew to about 1.2 to  $1.5\mu\text{m}$  at the highest temperature after 120 seconds. [37] The growth of the intermetallic phase not only reduces the solderability of the component, but when it occurs after the component has been soldered to the board, the increased intermetallic layer thickness will affect the mechanical properties of the solder joint as the intermetallic layer is more brittle than the solder in the joint fillet. Thus, as the solder joint ages the thickening intermetallic layer will reduce the fatigue life. [39]

Many companies have used accelerated temperature cycling to try and determine the reliability of a solder-joint under extreme conditions while many others use destructive testing by vibration. Figure 2.15 is the result of such a study carried out by a laboratory in Tokyo in 2007 [30] that found that the solder joint reliability of SnPb solders was very similar to that of SN100C (SnCuNiGe) when comparing all three alloys.



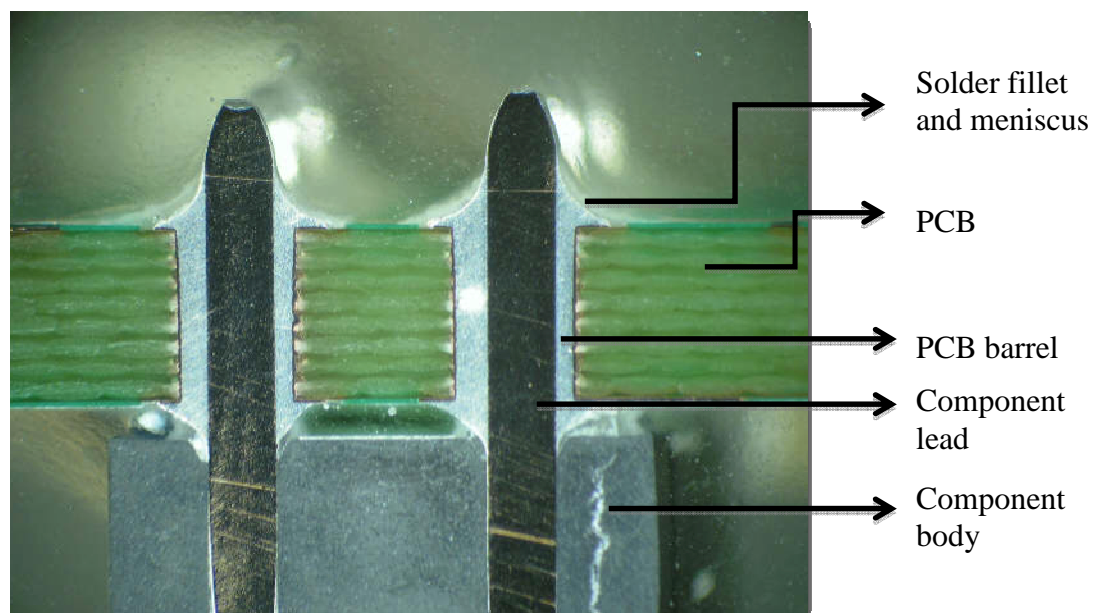
**Figure 2.15 Weibull graph of alloys - destruction analysis by vibration testing [30]**

It can be seen that for this configuration in Figure 2.15, SnPb and SnCuNiGe (SN100C) solders show better performance than the SAC solder. The y-axis is the cumulative percentage failures that resulted because of the number of vibration cycles on the x-axis. For example, at 10,000 vibration cycles there were less than 2% cumulative failures for SnPb solder joints, approximately 4% cumulative failures for SnCuNiGe (SN100C) and approximately 20% cumulative failures for SAC solder joints. [30] Based on this analysis

SN100C is a comparable alloy to SnPb and for reasons explained above, was considered in this project as the principle alloy in the Wetting Balance investigation.

### 2.2.2 The Solder Joint

For electronics industry soldering applications, a solder joint with a satisfactory fillet formation is desired for minimum stress concentration. [40] A cross section of a 'preferred' pin-in-paste through-hole solder joint can be seen in Figure 2.14. Solder joint formation is the culmination of the entire process, i.e. solder paste printing, surface mount placement and reflow soldering. Solder paste printing for pin-in-paste application is the process of automatically printing solder paste into a PCB through-hole using a stencil after which the component is automatically placed into the paste deposit. A reflow process is used to solidify the paste within the barrel of the PCB and attach the component thus creating a metallurgical solder-joint and forming a good meniscus as seen in Figure 2.16. [41]



**Figure 2.16 Cross section of a 0.9mm diameter Through Hole Solder joint [42]**

Pin-in-paste soldering is another alternative to wave solder because it is a much cheaper process. Many companies are move from the traditional wave solder process to pin-in-paste soldering due to the cost benefits and also the requirement for less floor space due to the removal of a process step – wave soldering. [41]

Regardless of the quality of the design, or any other single portion of the process, if high-quality reliable solder joints are not formed, the final product is not reliable. One of the key requirements for a reliable solder-joint is the strength of the joint formed. [41]



### 2.2.2.1 Solder Joint Strength

An assessment of the solder joint strength between the three alloys used in this project, SnPb, SAC305, SN100C, was conducted in a laboratory in Ireland [42] showed the shear strength (Newton) to be very comparable, see Table 2.2. Large Electrolyte capacitors and small 1206 resistors were assessed with the aforementioned alloys of solder-pastes.

**Table 2.3 Shear test results for SAC305, SN100C and SnPb alloys [43]**

<b>Component Type</b>	<b>Shear Test 1 (N)</b>	<b>Shear Test 2 (N)</b>	<b>Shear Test 3 (N)</b>	<b>Shear Test 4 (N)</b>	<b>Shear Test 5 (N)</b>	<b>Min (N)</b>	<b>Max (N)</b>	<b>Average (N)</b>
<b>Large Capacitor (SAC305)</b>	<b>93.6</b>	<b>90.3</b>	<b>98.6</b>	<b>96.9</b>	<b>97.8</b>	<b>90.3</b>	<b>98.6</b>	<b>95.4</b>
<b>Large Capacitor (SN100C)</b>	97.3	91.2	99.4	96.1	95.9	91.2	99.4	<b>96.0</b>
<b>Large Capacitor (SnPb)</b>	111.1	97.3	101.3	103.8	104.7	97.3	111.1	<b>103.6</b>
<b>Small Resistor (SAC305)</b>	<b>43.4</b>	<b>40.1</b>	<b>42.6</b>	<b>41.3</b>	<b>40.6</b>	<b>40.1</b>	<b>43.4</b>	<b>41.6</b>
<b>Small Resistor (SN100C)</b>	43.8	42.3	44.1	40.2	42.8	40.2	44.1	<b>42.6</b>
<b>Small Resistor (SnPb)</b>	42.8	44.6	40.7	41.6	40.9	40.7	44.6	<b>42.1</b>

Once there is sufficient evidence to show the close relationship between solder joint strength for SnPb and the replacement lead-free alloys such as SAC305 and SN100C, there remains one important requirement to be fulfilled which is the soldering ability of the component leads. If one can guarantee with a certain degree of confidence, good soldering components, the solder joint strength and reliability will follow because one of the main requirements is fulfilled. [43]

Having a reliable Wetting Balance test that will detect all poor solderability components and avoid any failures that may occur in the electronic PCB while in use is of paramount importance. A Wetting Balance test is the key to ensuring all poor soldering components are detected prior to use in series production, once the test itself is fully understood and optimised. This project will assess the Wetting Balance test in terms of its reliability and put mathematical models in place that will assist in the detection of poor soldering components.



### 2.2.3 Fluxes

Soldering can only be performed successfully if the surfaces to be wetted by the solders are clean (free from oxides). All soldering methods therefore use a means of cleaning these surfaces prior to soldering, in most cases a flux. The word “flux” comes from the Latin meaning “flow”, and indeed the main role of the flux is to promote flow of solder. A flux promotes solder wetting of the base materials:

- To provide clean oxide free surfaces of the solid PCB by dissolving or breaking up the surface layer.
- To retain the oxide free nature of the hot PCB ahead of the wetting front.
- To influence the surface tension equilibrium such that the Contact Angle is reduced.
- To retard oxidation of the molten solder surface during flow and cooling.
- It must be either non-corrosive or easily removable.
- It must act as a heat transfer medium to ensure that the parts to be joined reach a temperature high enough to form a bond. [44]

Successful formation of any solder joint requires that the liquid solder make contact with the metal to which it is to be joined, so that wetting can be initiated. Unfortunately, almost all of the metals involved in soldering are oxidised during the elevated temperatures in air. This prevents metal-to-metal contact as well as the wetting and formation of a metallurgical bond, unless the oxides are removed. [44] An experiment carried out by the University of Denmark [45] found that the amount of residues decreased as the temperature increased, see Figure 2.17.

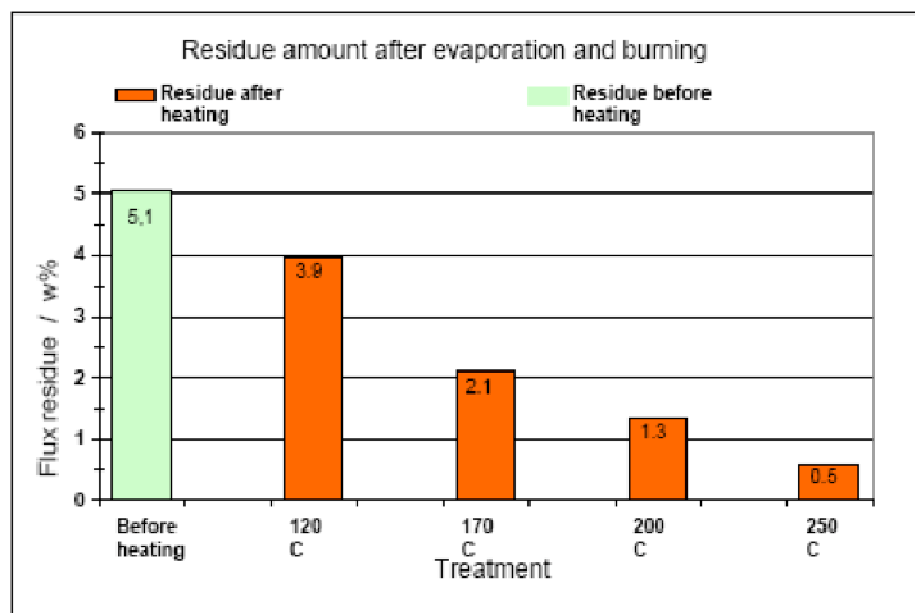
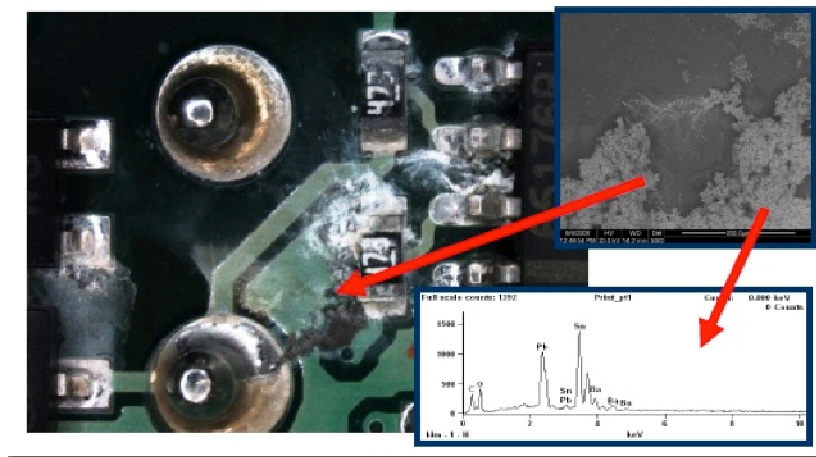


Figure 2.17 Flux residue amounts after heating to various temperatures [45]

One of the main concerns for engineers when choosing a flux is the aggressive nature of the residues that may be left behind after the flux, if the temperature of the soldering process is not sufficient enough to burn them off. [45]

Figure 2.18 is an image of flux residues after the soldering process and also the EDX (Energy-dispersive X-ray) Spectrum. These types of residues can result in corrosion of the electronics over time that eventually will lead to failure. Corrosion reliability is a serious issue today for electronic devices due to factors such as miniaturisation of components. Process related residues on PCB surfaces are a key factor in accelerating corrosion. [45]



**Figure 2.18 Flux residue on electronic and EDX spectrum [45]**

Fluxes for soldering electronics fall into the following categories, rosin based and so called water-soluble (the flux itself is not soluble in water however the residue left after soldering is). There are two important specifications for fluxes used in electronics, J-STD-004 and MIL-F-14256E. J-STD-004 has three assembly classes, Class 1 – Consumer products, Class 2 – General in industrial, Class 3 – High reliability and military electronics. Both specifications have very similar test methods required to characterise flux and flux performance. [46]

Throughout this project the same flux was used when assessing the Dip & Look and Wetting Balance tests. This was a standard production flux of Class 1. The supplier of the Wetting Balance machine do provide samples of fluxes but these were not considered because the author wanted to keep as many variables to a minimum as much as possible.

#### 2.2.4 Summary of Key Research Points

- Soldering depends on certain fundamental parameters and the issues associated with each such as:
  - Solder Alloy – There are three alloys used in this project, SnPb (lead), and two lead-free alloys - SAC305 and SN100C. In terms of visual

appearance SnPb and SN100C are very similar. SAC305 along with many other lead-free alloys have a dull grey appearance. For this research when setting up programs on the Wetting Balance machine it is important to know the density of each alloy because the Solder Density is a key factor when calculating the maximum force. The solder joint strength for all three alloys is very comparable and this was evident from Table 2.3. One of the key requirements for a reliable solder-joint is the strength of the joint formed.

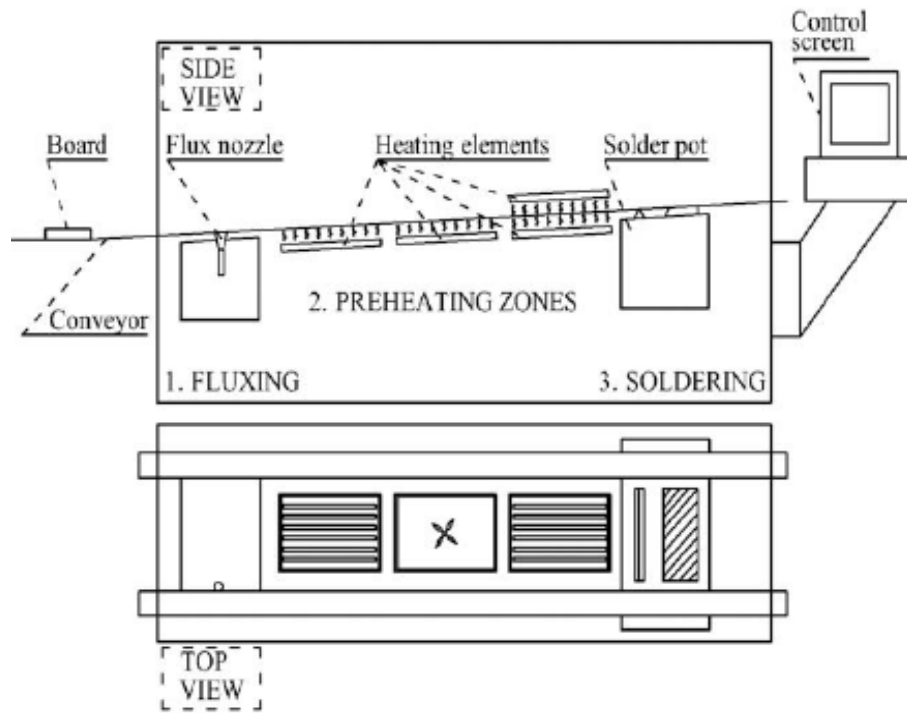
- Flux – To minimise the variables within this project, the flux used remained constant throughout the project. The flux is a standard production flux used in industry. Flux is required to ensure the test specimens are clean before testing to minimise any impact of oxides on the results.
- The reflow characteristics for each alloy will be considered when setting up the Wetting Balance programs for each alloy. It is important to ensure the correct alloy characteristics are used to get accurate results for the maximum force,  $F_{max}$ .

## **2.3 Soldering Methods**

A soldering iron is mostly used to repair defective solder joints on components using solder in the form of a wire. The heat is supplied using the soldering iron and the flux is manually applied. The manual intervention of an operator soldering puts in doubt the repeatability of parameters during soldering with hand held equipment. There are two-principle methods of mass soldering in use worldwide. These are Wave and Reflow soldering applications. [47]

### **2.3.1 Wave Soldering**

Wave soldering is a mass soldering technique used to solder through-hole (TH) components. Also assemblies of mixed technology with both through-hole and surface mount devices (SMD) may be soldered in wave soldering process. The board is conveyed through the process of applying flux, preheating and soldering. In a typical setup the PCB, on which components have been placed, is transported in a pallet (carrier) through a wave-soldering machine by using an automatic conveyor. There are open areas on the underside of the pallet so that the underside of the board is exposed to the processing stages. [47] The wave soldering process consists of three main stages as shown in Figure 2.19.



**Figure 2.19 Wave Soldering Machine Process [47]**

(1) At the first stage, the surface of the PCB assembly, with through hole components already placed in the PCB, moving along the conveyor in the pallet is wetted by the fluxing system containing the flux pump and flux nozzle which sprays the flux. The main purpose of fluxing is to improve the wetting of surfaces and to protect the metal parts from oxidation during soldering. [47]

(2) The second stage is for pre-heating the PCB in heating zones that can include, for instance, convection, tubular resistance or infrared types of heating elements. Pre-heating activates the flux, reduces the thermal shock resulting from thermal expansion and, in addition, removes the possible moisture and undesired substances from the surface of the PCB. [47]

(3) At the third and final stage, the components are soldered to the board using the solder wave, where the wave-like molten solder is pumped through an opening on the pallet to the underside of the board. A smaller and more intensive chip wave can also be used in addition to the main solder wave to get the solder into the narrowest spaces between the components. [47]

### 2.3.2 Reflow Soldering

In order to eliminate the problems encountered in wave soldering surface mount components, i.e. for large surface mount components and fine pitch components, reflow soldering technology was introduced to the surface mount process. Here the solder powder and flux are pre-blended to form a solder paste. This solder paste is then deposited, usually

through stencil printing, onto the Printed Circuit Board pads where the surface mount components are subsequently placed. This tacky solder paste serves as a temporary glue and holds surface mount components in place prior to the reflow soldering process. The populated boards are then put through the reflow oven where the solder paste is reflowed, forming solder joints on the components. The temperature settings on the reflow oven are determined using the reflow soldering profile specific to the PCB and components. [48]

#### **2.3.2.1 Reflow Soldering Profile**

The soldering temperature profile consists of four phases, preheat, soak, reflow and cooling. To set-up a soldering profile parameters like temperature, cooling speed, conveyor speed and fan speed for each zone must be considered. [48] Figures 2.12 and 2.13 are typical reflow profiles for a Pb process and Pb-free process respectively.

##### **2.3.2.1.1 Preheat Zone**

During the pre-heat phase the solvents evaporates from the solder paste. If the temperature rises too rapid during the pre-heat, two problems can occur. Firstly solder balls can be spread when the solvents burst through the flux surface membrane. This is called solder balling. Furthermore the solder paste can slump, because of a rapid temperature rise changes the viscosity of the solder paste. This will result in bridging. [48]

##### **2.3.2.1.2 Soak Zone**

During the soak phase the temperature rises slowly. The purpose is to activate the flux and to equalise the temperatures on the PCB. Most fluxes activate at around 145°C. [48]

##### **2.3.2.1.3 Reflow Zone**

During the reflow phase the temperature is increased to melt the solder paste alloy and then form the solder joints. The peak reflow temperature for SnPb is typically in the range of 210°C to 225°C and for Pb-free alloys such as SAC and SN100C the peak temperature may approach 240°C to 260°C. [48]

##### **2.3.2.1.4 Cooling Zone**

The cooling phase is an equally important factor to the other three phases. The importance of the cooling is often underestimated but the strength of the finished solder joint is depended on the speed of cooling. For the solder joint to perform a strong bonding between the solder pad and the component terminal, the cooling should be as fast as possible. [48]

## 2.4 Solderability Test Methods

There exists, for the solderable surfaces of printed circuit boards and components, a number of methods for the measurement of wetting parameters that act as a guide to the solderability in production assembly. The development of a variety of tests has arisen because of the complex character of the property of solderability and the lack of reference materials of standard solderability values. Adding to the fact that there is no one test used throughout the industry, there is often no standardised procedure for carrying out the tests and no consensus as to how the output data can be used to physically describe the property of solderability in terms of the requirements of the electronics' industry. [49]

The main solderability test methods researched in this project are:

- Dip & Look test
- Wetting Balance test method

### 2.4.1 Dip & Look Test

In this test method a small bath of solder of given composition and purity is maintained at a constant temperature. The test component and purity is maintained at a constant temperature. The test component is then fluxed and preheated before dipping into the molten solder at a known rate of immersion to a given depth, for a specified time and then withdrawing it, again at a known rate. It is the simplest of all solderability tests to perform. The difficulty of this test lies in the subjectivity of the subsequent visual assessment. [50]

#### 2.4.1.1 Procedure for Dip & Look Test

The component is best held in a stainless steel clip or tweezers and the whole component completely immersed in the flux to be used in the manufacturing process. Any drops of excess flux are then removed by contact with an absorbent paper. After the oxide file has been removed from the surface of solder bath, the specimen is immersed in the liquid solder. The immersion can be performed by hand but is best achieved by a controlled mechanical apparatus, such as a Wetting Balance machine, providing a constant immersion speed as specified. The dwell time in the solder is also specified. When removed at a specified speed the component is then visually inspected using a microscope. The Dip & Look test is a single-condition test method and gives no indication of the speed of wetting. It does however show whether adequate wetting can be achieved within a specified time. [50]

The Dip & Look test is currently the most widely used in industry. Visual inspection remains the dominant method of assessing component lead solderability and finished board

solder joint quality. The drawbacks of the test are that the information gained is highly subjective and it describes the results of the soldering rather than the act of soldering. Therefore discrepancies in test results occur often and arguments between manufacturers and users are frequent. Research carried out by Woods in 2007 [51] found that no possible solderable failure could be made in order to test the credentials of the Dip & Look test. The 95% coverage level was achieved on all test specimens and this lead to the conclusion that this test serves no purpose in determining a component or PCB's solderability. [51]

After extensive soldering analysis involving 30,000 individual tests, imminent new IPC standards recognise that Wetting Balance force measurement and globule testing is better than traditional 'Dip & Look' manual judgments for quantitatively determining solderability to the precision required so that adjustment to the soldering process becomes unnecessary. [52]

The main problem with the traditional Dip & Look technique - which is highly popular, quick and inexpensive - is its lack of adequate repeatability and according to the IPC:

*"Users who believe that the 'Dip & Look' methodology has a respectable Gauge R and R would be in for an extreme shock".*

*"The IPC committees have also voted that no new solderability test methods will be introduced into the standards without a demonstrated, industry acceptable Gauge R and R value." [52]*

The IEC recommends Wetting Balance force measurement and globule testing, and attempts are been made to harmonise standard documents, to provide acceptable Gauge R and R to its defined methodology. [52]

### **2.4.2 Wetting Balance Test**

The IPC/EIA J-STD-003A Document states that:

*"The solderability determination is made to verify that the printed board fabrication processes and subsequent storage have had no adverse effect on the solderability of those portions of the printed board intended to be soldered. This is determined by evaluation of the solderability specimen portion of a board or representative coupon, which has been processed as part of the panel of boards and subsequently removed for testing per the method selected. [53]*

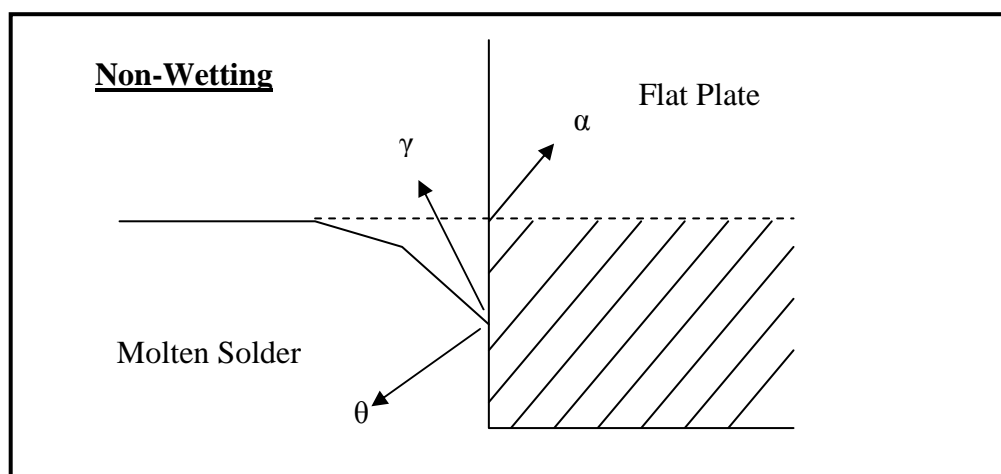
The solderability of a Printed Circuit Board or components metallic terminations is a critical parameter in any soldering operation because it represents the likelihood of that termination forming a good alloy with the solder and a high quality solder fillet. [53]

The Wetting Balance machine measures the vertical forces of buoyancy and surface tension, as a fluxed test piece is immersed into a bath of molten solder. The most common

electronics terminations include component leads and footprints, the pads of solder lands, and plated through holes (PTHs). Unless these offer a reliably consistent level of solderability, soldering defect rates will be high, along with rework, scrapping and field failure costs. As PCBs and components continue to become smaller and finer pitched, coupled with the widespread use of less active fluxes, the soldering process window narrows and the impact of poor solderability increases. Although components and PCBs are generally assembled from parts of known good solderability, there is no way of guaranteeing this without testing, especially given that the prime cause of poor solderability is how well a part has been stored. The most effective quantitative method for measuring, testing and recording solderability is the Wetting Balance. A transducer converts the wetting force into an analogue signal. This signal may be taken directly onto an X/T recorder, or may be digitised and analysed by a computer. The digital signal is used to generate the force-time curve, and is analysed to find the required forces and times from the force-time curve. [54]

#### 2.4.2.1 The Wetting Forces

The Wetting Balance or Meniscograph is used to access the solderability of components using dipping or stationary mode, as it is sometimes called. In this mode the component is dipped at such a speed that no wetting or very little wetting occurs, as the component is immersed into the solder, and the vertical force is monitored while the component is held stationary in the solder bath. Figure 2.20 shows a flat plate immersed in a bath of molten solder, at the start of the test. [55]



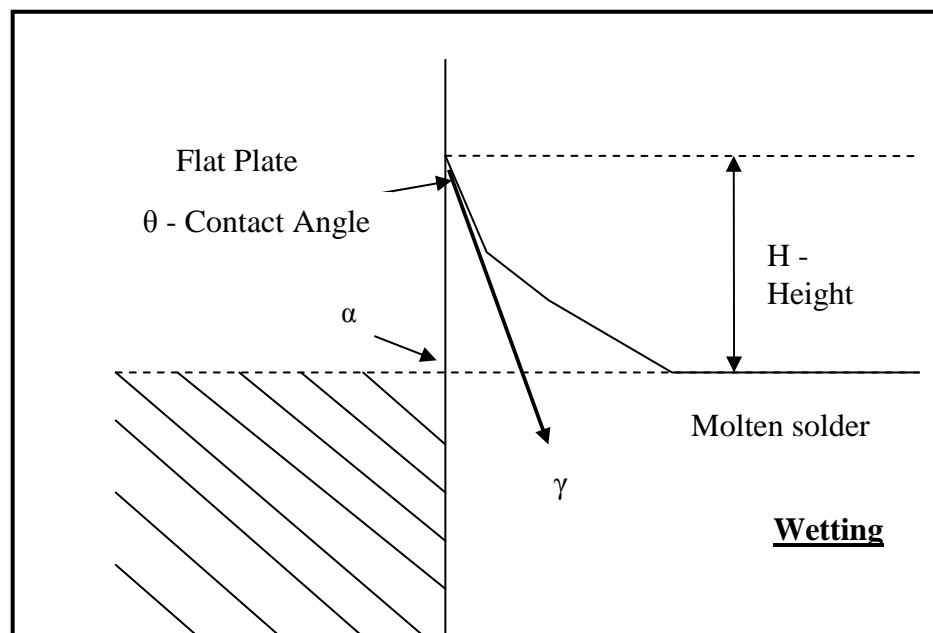
**Figure 2.20 Wetting of a flat plate by molten solder [55]**

The plate has been immersed at 20 or 25mm/sec and as yet no soldering has occurred. The solder surface has been depressed, and the surface tension force is trying to push the plate out of the solder bath, producing an upward or rejecting force. The surface tension force  $\gamma$



acts tangentially to the solder surface, at an angle  $\theta$  between the solder and the flat plate. The Contact Angle,  $\theta$ , is always measured inside the molten solder. During immersion the flat plate displaces, a volume of solder, equal to the immersed volume of the plate. This displacement produced a buoyancy or Archimedes force, also acting upwards and rejecting the plate from the solder bath. The plate is dipped vertically into the molten solder at an angle  $\alpha$  to the horizontal. Once soldering commences, the solder starts to climb back up the plate until the solder surface is again horizontal. At this point the solder surface tension force is acting horizontally along the bath surface. However, the buoyancy force is still present, and this is now the only vertical force acting on the plate. [55]

Figure 2.21 shows the vertical plate at the end of the Wetting Balance test, when soldering is complete. The surface tension force is now acting downwards, trying to pull the plate down into the solder bath. The Contact Angle,  $\theta$ , is now less than  $90^\circ$  and the plate is considered to have wetted. While the Contact Angle is greater than  $90^\circ$ , as it was at the start of the test, the plate is considered not to have wetted. [55]



**Figure 2.21 Wetting of a vertical plate by molten solder [55]**

If the plate has good solderability the solder will rise above the bath surface to a height,  $H$ . The height of rise, and hence the wetting force, measured by the Wetting Balance, will depend on the solderability of the plate. The theoretical maximum height of rise is determined by the surface tension and density of molten solder. [55]

The vertical force recorded by the Wetting Balance measures the changing vertical component of the surface tension force, as the solder rises from below the bath surface to above the bath surface, as the plate solders. The Wetting Balance is actually showing how the Contact Angle, between the molten solder and the flat plate, changes during test time.

This is because the vertical force is proportional to the cosine of the Contact Angle. Equation 2.4 gives the vertical force measured by the Wetting Balance:

$$F = \gamma p \cos\theta - g \rho v \dots\dots\dots \text{Eq-2.4 [56]}$$

Where:

$F$  = maximum force (mN)

$\gamma$  = surface tension of the molten solder under flux (mN/mm)

$p$  = specimen perimeter (mm)

$g$  = gravitational acceleration ( $9.81\text{m/s}^2$ )

$\rho$  = molten solder density ( $\text{g/mm}^3$ )

$v$  = specimen immersed volume (mm)

$\theta$  = Contact Angle ( $^\circ\text{C}$ )

The term on the right of the equation  $g\rho v$  is the calculated buoyancy force, experienced by the immersed plate. The volume of the solder that has been displaced, and may be considered to remain constant during the test determines this. The wetting force is represented by  $\gamma p \cos \theta$ . The longer the specimen perimeter, the greater the area that is available to be soldered, and therefore the higher wetting force. The specimen perimeter and the surface tension is considered to remain constant during the Wetting Balance test and so the only factor changing during the test is the Contact Angle,  $\theta$ . [57] The Contact Angle formula will be used in Chapter 8 as part of the analysis of results.

#### **2.4.2.2 The Wetting Balance Curve**

Figure 2.22 shows a typical Wetting Balance curve, where force is shown on the vertical axis and time is shown on the horizontal axis. Before the start of the test the Wetting Balance machine automatically calculates the weight of the specimen and the specimen holder, so that the test starts at zero force line. [58][58][60]

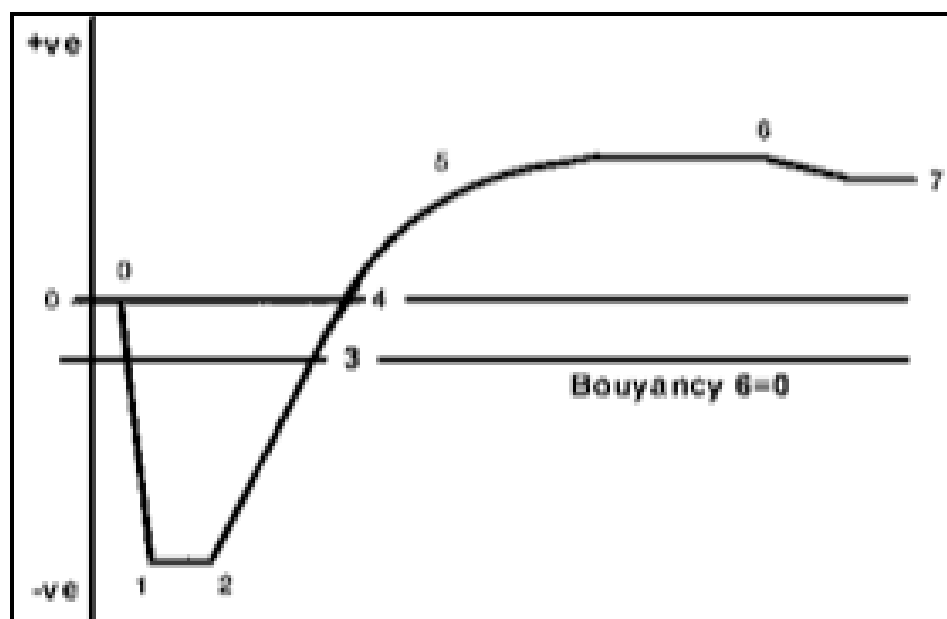
Non-wetting or rejected forces are shown as negative, where the cosine of  $\theta$  is less than zero, and wetting forces are shown as positive, where the cosine of  $\theta$  is greater than zero.

- At Point 0 – the solder bath is driven up to make contact with the specimen. This is considered to be the starting point of the test. The bath continues to drive up until the specimen is fully immersed to the pre-set immersion depth. [58][58][60]
- At Point 1 – The bath stops and the specimen is now fully immersed. Specimens with low thermal demand and good solderability will start to solder immediately. Some may even have started to solder during immersion, despite the high immersion speed, especially specimens with fusible coatings and good solderability. [58][58][60]

- At Point 2 – Specimens with high thermal demand or specimens tested with water soluble fluxes may not start to solder until this point. The difference between points 1 and 2 is the time taken for the specimen to reach soldering temperature or for the solvent to evaporate from the flux, and the flux to be activated. [58][58][60]

Once soldering commences the solder rises back up the specimen, the Contact Angle inside the solder decreases and the negative wetting force starts to decline. [58][58][60]

- At Point 3 – the solder surface has returned too horizontal and the Contact Angle has fallen to  $90^\circ$ . The surface tension force is now acting horizontally and so has no effect vertically. The only vertical force still acting is the buoyancy force. The buoyancy force is the up-thrust exerted by the displacement of a volume of solder, equal to the weight of the volume of solder displaced by the specimen immersed below the solder surface. The solder now starts to climb above the solder bath surface and the Contact Angle begins to decrease from  $90^\circ$ . Point 3 on Figure 2.22 is representative of  $T_a$ , time to buoyancy that should be reached within 0.6 seconds as per the international standards. [58][58][60]
- At Point 4 – the downward force from the solder surface tension is exactly equal to the buoyancy force, and a net force of zero is obtained. Point 4 is representative of  $T_b$ , time to cross the zero line which as stated in the international standards much be reached with 1 second. [58][58][60]
- At Point 5 – The solder continues to rise above the bath surface and at this point, the force after a specific immersion time, usually 2 seconds as per the J-STD-002C, is often used as a measure of the solderability of the specimen. [58][58][60]



**Figure 2.22 Wetting Balance Curve – Force (mN) vs. Time (sec) [57]**

- At Point 6 – The maximum wetting force has been reached, the solder has reached its maximum height up the specimen, above the surface of the solder bath, and the Contact Angle has reached its minimum value. If dewetting occurs the force will decline as the solder retreats from the specimen and the Contact Angle increases. Point 6 is representative of  $F_{max}$ , the maximum force reached during the test. [58][58][60]

A similar reduction in the wetting force will be obtained if the plating material on the specimen dissolves, or if a heavy fusible coating on the specimen melts above the solder meniscus. [58][58][60]

- At Point 7 – Generally this point will be at the same force level as the maximum wetting force, indicating a stable wetting condition. At this point the dwell period ends and the bath drives away from the specimen. The test is considered to end at this point, as it is generally accepted that little useful information is available from the spike obtained as the specimen is pulled out of the solder bath. [58][58][60]

#### **2.4.2.3 Summary of Key Research Points**

The two main solderability tests considered in the project are the Dip & Look and Wetting Balance tests.

- Dip & Look – is the most commonly used solderability test for most component manufacturers. It is a quick test that involves a manual dipping of a component into a solder bath and visually inspecting for a 95% solder coverage. It does not provide any significant information such a wetting force or speed compared to the Wetting Balance test.
- The Wetting Balance test automatically measures vertical forces of buoyancy and surface tension for the test specimen. One can calculate the Contact Angle using the force reading from the Wetting Balance machine and the wetting force equation:
  - $F = \gamma p \cos \theta - g \rho v$
- The Wetting Balance graph is another key research topic because it graphically explains the different important sections on the graph as shown in Figure 2.22. The time to buoyancy and time to cross the zero line are two responses that are specified within the international standards, as been 0.6 seconds and 1 second respectively.

## 2.5 Standardised Test Methods

The use of the Wetting Balance and the Dip & Look tests methods for testing the solderability of component terminations have been included in a number of national and international standards. This section briefly reviews the test conditions and requirements of some of the commonly used standard methods. The four standards used for the Dip & Look and the Wetting Balance investigations are:

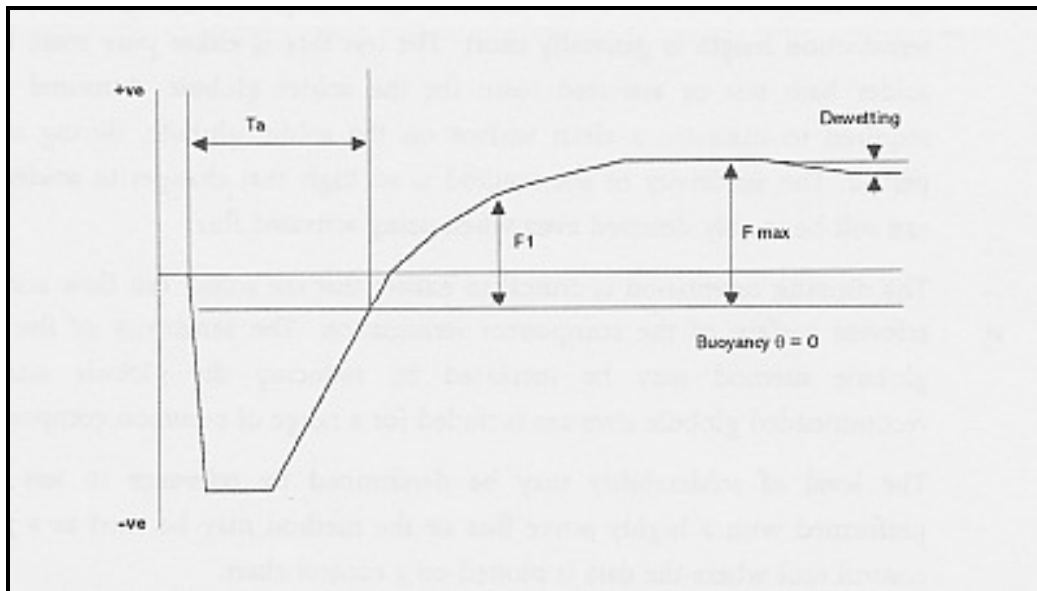
1. International Standard, IEC-60068-2-54 Environmental Testing – Part 2-54: Tests – Test Ta: Solderability testing of electronic components by the Wetting Balance method.
2. International Standard, IEC-60068-2-69 Environmental testing of electronic components for surface-mount devices by the Wetting Balance method.
3. International Standard, J-STD-002C Solderability Test for Component Leads, Terminations, Lugs, Terminals and Wires.
4. International Standard, J-STD-004 Requirements for Soldering Fluxes.

### 2.5.1 IEC 60068-2-54

The Wetting Balance test method is included as part of the Basic Environmental Test Procedures, Part 2: Tests-Ta: Soldering.

The procedure uses a test temperature of 235°C and a non-activated rosin flux. This is a common practice in all solderability test methods where a low testing temperature and weak flux are used to carry out the test. This is to build a safety margin into the test method because the tests will generally only be carried out on a sample from a batch, and obviously it is very unlikely that the worst components will be included in the test sample. If the sample passes using the weak test conditions then the production run should be satisfactory, when a higher soldering temperature and a more active flux will be used. [60]

This method uses an immersion speed of 15 to 25mm/s and an immersion depth of 2 to 5 mm. The use of shallow immersion depths will give poor heat transfer, and lead to variable delay before the onset of wetting. The deeper the immersion the greater the heat-transfer to the specimen, and therefore the shorter delay before the onset of wetting. The greater the immersion depth the higher the buoyancy therefore the further the curve will be displaced downwards away from the zero line. If the immersion depth is sufficiently high, the wetting curve may remain below the zero force line for the entire test period. The test method uses the time for the Wetting Balance curve to re-cross the buoyancy line (Ta in Figure 2.23) as the time for the onset of wetting. This is when the solder bath surface has returned to the horizontal, and the solder Contact Angle has fallen to 90°. [60]



**Figure 2.23 Wetting Balance Curve for  $T_a$ , IEC 68-2-54 [60]**

The test method then uses a minimum value for the wetting force, at a specified time of typically two seconds, expressed as a percentage of the theoretical maximum or reference wetting force, as a measure of the progress of wetting. The reference wetting force is established by finding the maximum wetting force that can be obtained on a specimen that has been pre-tinned using an active flux. The pre-tinning procedure is repeated until the maximum wetting force does not increase any further. The stability of wetting is evaluated by measuring the decline in force, if any, from the maximum wetting force, to the force at the end of the test period. This decline in force is expressed as a percentage of the maximum soldering force. Note that all forces are measured from the buoyancy line, when using this method. [60]

### **2.5.2 IEC 60068-2-69**

The component is suspended from the balance and after fluxing the termination is brought into contact with the surface of a solder bath or the apex of a solder globule. The resultant forces of buoyancy and surface tension are monitored and displayed as force against time. The solderability is determined from the rate and extent of the wetting force. [61]

This method uses low immersion depths with slow dipping speeds, as the termination length is generally short. The test flux is either pure rosin for the solder bath test or activated rosin for the solder globule. Activated flux is required to maintain a clean surface on the solder globule, during the test period. The sensitivity of the method is so high that changes in solderability can still be readily detected even when using activated flux. [61]

The dipping orientation is critical to ensure that the solder can flow across the relevant surface of the component termination. Reducing the globule size may increase the

sensitivity of the solder globule method, and recommended globule sizes are included for a range of common components. The level of solderability may be determined by reference to test results performed with a highly active flux or the method may be used as a process control tool where the data is plotted on a control chart. [61]

### **2.5.3 ANSI/J-STD-002 Test C**

This method is for both surface mounted and through-hole mounted leaded components. The test is carried out using a flux and a solder bath temperature of 245°C. The class of component being tested determines the speed and depth of immersion used. Through-hole mounted components are dipped vertically into the solder bath: that is, use an entry angle of 90°. Leaded surface mounted components are immersed using an entry angle of 45° to 70°. A complete side of leads is dipped simultaneously when testing a multi-leaded, surface mounted device. The requirements of this method are that the wetting force shall cross the buoyancy line in less than 1.0 second, and that the wetting force shall exceed 0.20 mN/mm at, or before, 2.5 seconds. The wetting force must also remain above 0.20 mN/mm at 4.5 sec from the start of the test. [7]

### **2.5.4 JESD-22-B102D Solderability**

This standard is focused towards the Dip & Look solderability test and provides information relating to the procedure and preconditioning requirements for both lead and lead-free testing. Instead of manually immersing the test specimen into the solder this standard states that the Wetting Balance machine should be used so the immersion speeds can be automatically controlled. A visual inspection of the test specimen after the test is required using magnification of 10x to 20x. Like all other test standards for the Dip and Look test, 95% solder coverage is the minimum requirement. [62]

### **2.5.5 Summary of Key Research Points**

Table 2.4 is a summary of the settings used in the four standards used for the experiment. The speed used in JESD-22-B102D, 19mm/sec – 31.8 mm/sec, could not be used on the Wetting Balance machine. When using the lower end of the setting, 19mm/sec, the machine went into error mode due to the fact that the immersion speed of the tower with the solder bath moving towards the component lead was too fast to allow the tower to stop when the sensor detected the component lead. This resulted in the solder bath and the component lead crashing into one another resulting in the error mode. The maximum allowable speed before any error occurred was determined by conducting a trial at different immersion speeds, and this was found to be 15mm/sec.

**Table 2.4 Summary of settings from International Standards**

International Standard	SnPb / Pb-Free	Solder Temperature	Immersion Speed	Immersion Depth	Dwell Time
J-STD-002C	SnPb	245 $\pm$ 5°C	1mm/sec - 5 mm/sec	0.1mm	5 $\pm$ 0.5 sec
J-STD-002C	Pb-Free	255 $\pm$ 5°C	1mm/sec - 5 mm/sec	0.1mm	5 $\pm$ 0.5 sec
JESD-22-B102D	SnPb	245 $\pm$ 5°C	25.4mm/sec $\pm$ 6.4mm/sec	Fully Immersed	5 $\pm$ 0.5 sec
JESD-22-B102D	Pb-Free	255 $\pm$ 5°C	25.4mm/sec $\pm$ 6.4mm/sec	Fully Immersed	5 $\pm$ 0.5 sec
IEC68-2-69	SnPb	235 $\pm$ 3°C	1mm/sec - 5 mm/sec	1mm	5 sec
IEC68-2-54	SnPb	235 $\pm$ 3°C	4mm/sec – 21mm/sec	2mm - 5mm	0 - 10sec
IEC68-2-54	Pb-Free	245 $\pm$ 3°C	4mm/sec – 21mm/sec	2mm - 5mm	0 - 10sec

The difference is clearly evident between each of the settings with the various international standards. The importance of understanding how these variations will impact the results from a Wetting Balance machine is crucial because currently there is too much tolerance associated with each standard. This will be investigated in detail within this project.

## 2.6 The MUST II Wetting Balance Machine

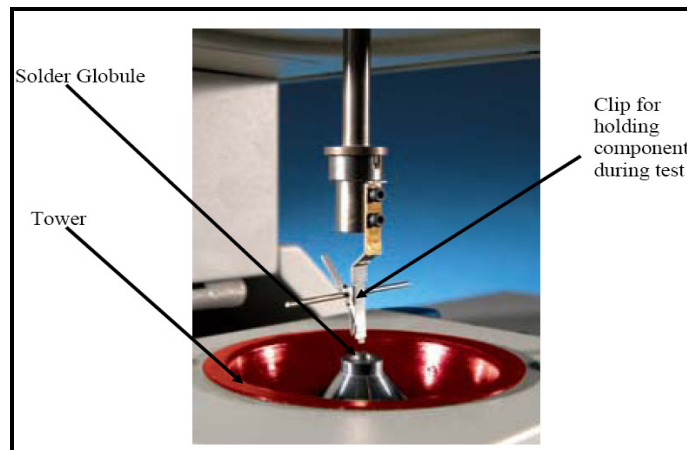
The most effective quantitative method for measuring, testing and recording solderability is the Wetting Balance. Although the type of Wetting Balance used for through-hole (TH) and surface mount (SM) components does differ, both are based on the same physical principles. In essence, a Wetting Balance exploits the fact that if a metallic body is dipped into a bath of molten solder, the weight and speed with which the solder meniscus climbs upwards on the body's immersed surface indicates how well the solder wets it and thus its solderability. In simple terms, the greater the solderability, the higher a meniscus will climb, which can be measured as a change in the vertical force acting on the suspended specimen. [63] The MUST System II, see Figure 2.24, is a high precision solderability tester for surface mount (SM) and through-hole (TH) components, as well as PCB pads and plated through-holes (PTHs or via's) on bare boards. [64]





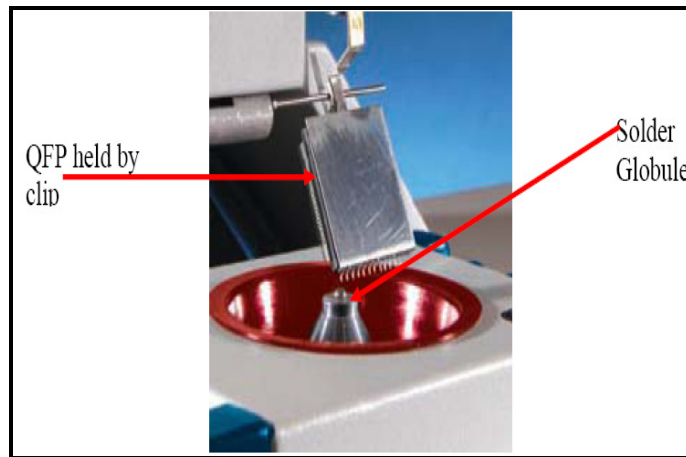
**Figure 2.24 MUST II Wetting Balance System 3 [64]**

It is also ideal for the laboratory testing of fluxes and other soldering materials. By eliminating problems associated with poor solderability, the MUST II can significantly improve product quality and yield large potential cost savings by lowering defect rates during the soldering process. [63]



**Figure 2.25 Tower with Solder Globule and Clip [64]**

In operation, the MUST II automatically detects a small solder bath (TH devices) or globule (SM) that is mounted on a computer-controlled worktable that is motor-driven in all three axes. This allows the instrument to align contact between the component terminations and solder precisely, guaranteeing test reproducibility and accuracy. Furthermore, for multi-leaded components, this allows the globule to be advanced automatically to each subsequent termination. In each case a component specific specimen clip, firmly holds the component in the correct position for testing, see Figure 2.26. [63]



**Figure 2.26 QFP held by clip on Wetting Balance Machine [64]**

The MUST II software guides users step-by-step through the entire test procedure using on-screen prompts. Testing is initiated by simply selecting the relevant component code and its associated set of test parameters (the MUST II stores hundreds of parameter and default test files of various SM components). This procedure ensures that each test is performed correctly. The MUST II Software then automatically calculates and records the component's solderability value and wetting curve, which can be presented as an immediate pass/fail for each device or stored for future reference. [64]

The measuring head uses a standard LVDT (Linear Variable Differential Transformer) to measure the vertical forces of surface tension and buoyancy acting on the component termination. Contact between the solder and the termination is detected at slow dipping speeds by monitoring the force signal at a high frequency. This allows electrically insulated terminations to be dipped into the solder globule or bath. At high dipping speeds, using the solder bath, electrical contact through the termination to the specimen clip is used to detect contact with the solder. [64]

The globule blocks are mounted on a motorised, computer controlled X-Y table. This system is used to set the start position of the test, which is recorded to a disk file with the test conditions and can be recalled and loaded onto the software before a batch of components are tested. The motorised table is also used to automatically advance along the side of a multi-leaded component. This enables individual leads on a multi-leaded device to be easily tested such as the 64 pin QFP's and 0.9mm diameter copper wires that were used in this report. [64]

## **2.7 Legislation and Directives**

The use of lead (Pb) has been widely accepted in the electronics industry, most notably the use of tin-lead (SnPb) solders to attach components to PCB's. These attachments also serve

as the electrical connection between the attached components and the PCB. The termination finishes on the components as well as the metallised pads on the PCB also use lead-based solders. [65]

From a study carried out by Robinson [65] in 2009, it was stated between twenty and twenty-five million tonnes per year of electronic waste such as electronic appliances are produced globally, with Europe, United States and Australia manufacturing the largest percentage. Electronic devices such as mobile phones and computers are disproportionately abundant because of their short lifespan and this had resulted in such a high volume of waste. In order to try and reduce this waste and also control its disposal, three major European Union (EU) Directives were established which serve as guides for reducing the toxic materials;

- Waste Electrical and Electronic Equipment (WEEE)
- Restriction of Certain Hazardous Substances (RoHS)
- End-of-Life Vehicle (ELV) [66]

### **2.7.1 WEEE – Waste Electrical and Electronic Equipment**

The WEEE Directive (or Directive 2002/96/EC) was adopted by the EU in October 2002 and came into effect in August 2005. It has since served as an important factor in reducing the amount of Electrical and Electronic Equipment (EEE) entering landfills and targets all the electronics industry and electronics imports supplying the EU such as;

- Large and Small Household Appliances
- IT Equipment and Telecommunications
- Radio, TV, Electro acoustic, Musical Instruments
- Lighting Equipment and Medical Equipment Systems
- Monitoring & Control Instruments
- Toys
- Electrical & Electronic Tools
- Automatic Dispensers [67]

Users of electrical and electronic equipment from private households have the possibility of returning Waste Electrical and Electronic Equipment free of charge back to the manufacturers. Producers finance the collection from collection facilities, as well as the treatment, recovery and disposal of WEEE. In order to give maximum effect to the concept of producer responsibility, producers are responsible for financing the management of the waste from their own products. [66] This directive has in a sense been successful in addressing the landfill issue, since today only about 13% of WEEE is registered as

disposed of as landfill or by incineration compared with the estimated 90% in the year 2000. Recycling rates have improved as it is now reported that 30% of WEEE is recycled and separated before incineration. [67]

### **2.7.2 RoHS – Restriction of Certain Hazardous Substances**

The EU issued Directive 2002/95/EC on the restriction and use of certain hazardous substances in electrical and electronic equipment. This is known as the RoHS or Restriction of Hazardous Substances, and came into effect on July 1<sup>st</sup> 2006. It was implemented to help protect human health and the environment by the recovery and disposal of electrical and electronic equipment. [68]

The RoHS Directive has banned the use of six substances in electrical and electronic equipment since July 1<sup>st</sup> 2006, namely lead (Pb), mercury (Hg) cadmium (Cd), hexavalent chromium (Cr (VI)), Polybrominated biphenyls (PBBs) and Polybrominated diphenyl ethers (PBDEs). [68] Any company who cannot comply with this legislation cannot trade within the EU. This had a huge impact on thousands of products that were on a continuous basis being supplied to the EU prior to the July 1<sup>st</sup> deadline whereby there is a requirement that these products be redesigned to remove the banned substances. For some companies this resulted in large investments for investigating new designs in order to comply with the EU market requirements. [69]

There is an allowable limit of less than 0.1% by weight placed on the use of the banned six substances. It is the responsibility of the manufacturer to ensure his/her sub-suppliers have given written assurances that the components / sub-assemblies do not exceed the threshold level of 0.1% weight. The manufacturers, in the event of an on-site inspection by enforcement authorities, must store the suppliers' compliance. [70]

### **2.7.3 ELV – End of Life Vehicle**

The Directive 2000/53/EC of the European Parliament and the Council on End-of-Life Vehicles (ELV) was adopted on 18<sup>th</sup> September 2000. This environmental legislation is based on Article 175 of the EU Treaty. Initially, member states were required to implement the Directive by 21<sup>st</sup> April 2002. However, all member states failed to communicate their national legislation before this deadline and the implementation date was extended a number of times. [71]

On the 23<sup>rd</sup> of February 2010 an amendment to Annex II of the ELV was made law whereby certain exemptions were extended. For the automotive industry, Section 8(a) of Annex II extended the changeover date to January 1<sup>st</sup> 2016:

*Material and Components;*

*Lead in solders to attach electrical and electronic components to electronic circuit boards and lead in finishes on terminations of components other than electrolyte aluminium capacitors, on component pins and on electronic circuit boards.*

*Scope and expiry date of the exemption;*

*Vehicles type approved before 1 January 2016 and spare parts for these vehicles.*  
[72]

Any automobiles put on the market after January 1<sup>st</sup> 2016 must have lead (Pb) eliminated and the spare parts for these vehicles must also be lead-free. All spare parts for vehicles put on the market prior to the January 1<sup>st</sup> 2016 deadline must be leaded (Pb), i.e. repair as produced. [72] [73] It remains to be seen if there will be a further extension of the ELV Directive deadline in the future. The only way manufacturing companies can prepare for the inevitable, is to investigate alternative soldering materials such as solder paste, wave solder and components with lead-free termination finishes. These alternative materials and components can be assessed in the products by doing test-to-failure testing and comparing the results to the current leaded materials. [71]

## **2.8 Design of Experiments**

Design of Experiment (DoE) is a structured, organised method that is used to determine the relationship between the different factors (X) affecting a process and the output of that process (Y). Sir Ronald A. Fisher, the renowned mathematician and geneticist, first developed this method in the 1920s and 1930. [74]

Design of Experiment involves designing a set of ten to twenty experiments, in which all relevant factors are varied systematically. When the results of these experiments are analysed, they help to identify optimal conditions, the factors that most influence the results, and those that do not, as well as details such as the existence of interactions and synergies between factors. [74]

Standard designs are well-known classes of experimental designs. They can be generated automatically as soon as you have decided on the objective, the number and nature of design variables, the nature of the responses and the number of experimental runs you can afford. Generating such a design will provide you with a list of all experiments you must perform, to gather enough information for your purposes. [75]

Design of Experiments (DoE) is widely used in research and development, where a large proportion of the resources go towards solving optimisation problems. The key to minimising optimisation costs is to conduct as few experiments as possible. DoE requires only a small set of experiments and thus helps to reduce cost. [76]

### **2.8.1 Factorial Experiment**

In statistics, a factorial experiment is an experiment whose design consists of two or more factors, each with discrete possible values or "levels", and whose experimental units take on all possible combinations of these levels across all such factors. A factorial design may also be called a fully-crossed design. Such an experiment allows studying the effect of each factor on the response variable, as well as the effects of interactions between factors on the response variable. [77] The numbers of factors used in this experiment was four:

- Solder Temperature
- Immersion Speed
- Immersion Depth
- Dwell Time

For the vast majority of factorial experiments, each factor has only two levels. For example, with two factors each taking two levels, a factorial experiment would have four treatment combinations in total, and is usually called a  $2 \times 2$  factorial design. Initially for D.O.E 1 the number of levels for each factor were two, i.e. high and low.

A factorial experiment allows for estimation of experimental error. The experiment can be replicated. Replication is more common for small experiments and is a very reliable way of assessing experimental error. Three replicates were used for this experiment. [78]

Factorial experiments can be used when there are more than two levels of each factor. However, the number of experimental runs required for three-level (or more) factorial designs will be considerably greater than for their two-level counterparts. Factorial designs are therefore less attractive if a researcher wishes to consider more than two levels. For DOE 2 a more in-depth analysis was required so three levels were used for each run combination. [78]

### **2.8.2 Analysis of Design of Experiment with Minitab**

When all the experimental runs were complete an analysis was required. The software used was Minitab version 13. Minitab is a computer program that was developed for statistics design and analysis in the U.S in 1972. It enables the analysis of the results of the D.O.E whether it is a Full Factorial or Fractional Factorial experiment by graphically displaying the results using Histograms, Main Effects and Interaction graphs or various other representations. Minitab will also help in the design of an experiment. [79]

### 2.8.3 Main Effects Plots

The effect of a factor is defined as the change in response produced by a change in the level of the factor. It is called the Main Effect because it refers to the primary factors in the study. [80] Figure 2.27 is an example of a Main Effects plot. It can be seen that as the Immersion speed increases from 1 to 5 the response Z (force) increases also. [81]

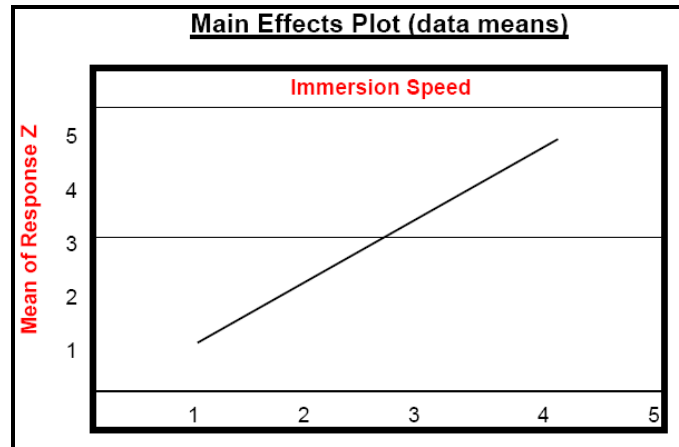


Figure 2.27 Main Effect Plot [81]

### 2.8.4 Interaction Plots

An Interaction plot is very similar to a Main Effect plot but shows the effect of two or more factors on a particular response. Figure 2.28 is an example. With reference to Solder Temp and Immersion Sp in Figure 2.28, it can be seen that by maintaining a constant solder temp of 250 (red broken line) and varying the Immersion Sp from 1 to 5, increases the result for Fmax. Similarly for Solder Temp and Immersion De by maintaining a constant Solder temp of 230 (black solid line), and varying the Immersion De from 0.25 to 0.5 dramatically increases Fmax. The Interaction plots are very helpful in determining the effect of changing the factors setting on the responses. [81]

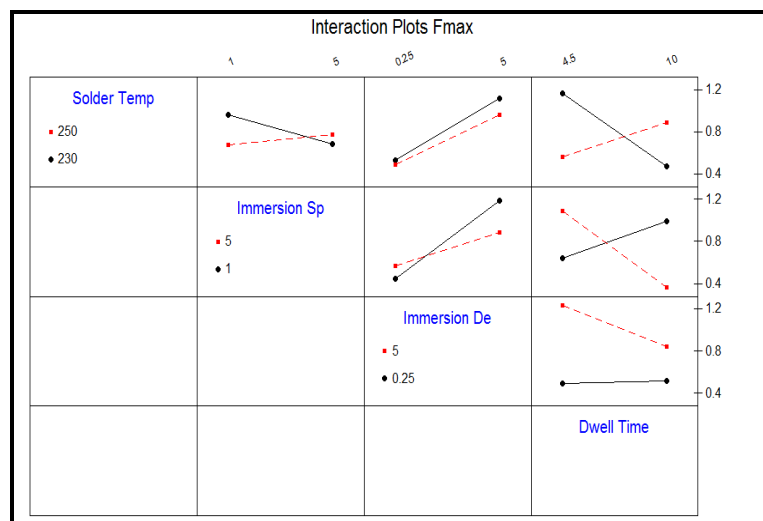


Figure 2.28 Interaction Plot [81]

### 2.8.5 Machine Capability

In order to assess the repeatability performance of the MUST II Wetting Balance machine it was decided to carry out a machine capability study. The supplier calibrated the MUST II system annually and before releasing the machine to production a very simple test was carried out to give a visual reading for repeatability. This test involved testing a known good component from production, repeating the test a number of times and assessing the results. For the purpose of this project, this type of analysis was not sufficient and it was decided to set-up a test to assess the machine capability using a copper wire of diameter 0.9mm and length 20mm. The reason for using the copper wire was to reduce as much as possible any variation that could be evident in a component leads solderability.

### 2.8.6 Machine Capability ( $C_{mk}$ )

$C_{mk}$  is the short-term capability examination to use for the acceptance of production equipment and machines and is also called machine capability examination. The machine capability determines the quality capability of new or modified machines and equipment (the test involves a random check of at least 50 parts). The minimum requirement for variations or “scatter” (s) is  $\bar{x} \pm 4$  standard deviations within a tolerance of  $C_{mk} > 1.33$ .

[80] Figure 2.29 is a process flow for carrying out a machine capability study. [82]

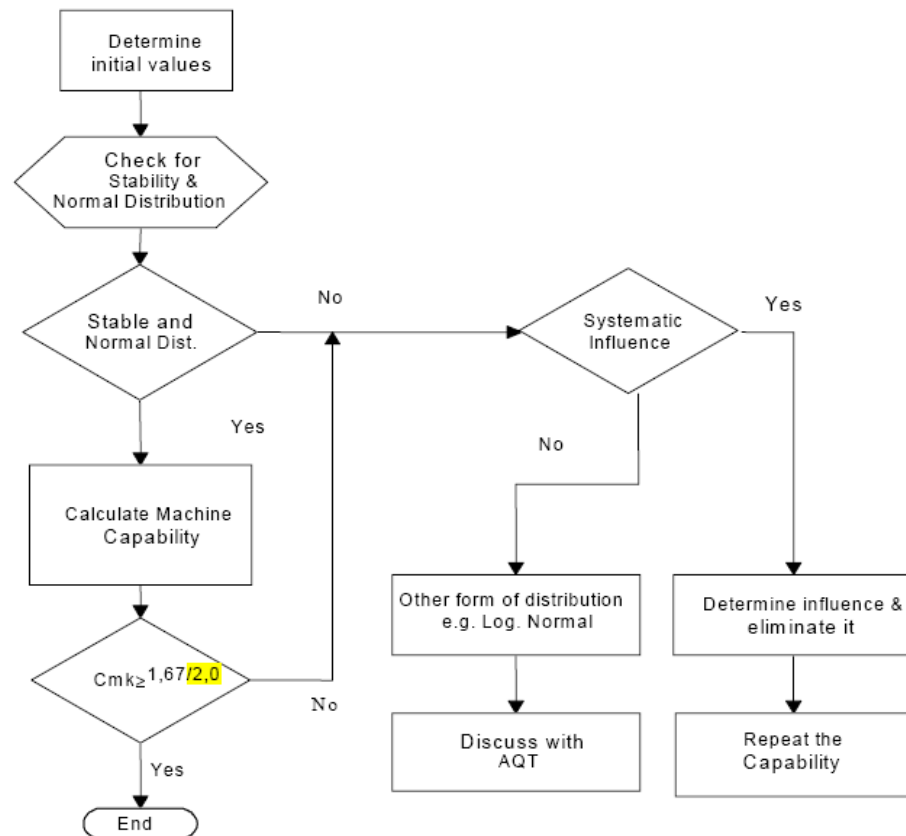


Figure 2.29 Process flow for carrying out machine capability studies [83]



## 2.9 Summary

This chapter has examined the requirements for soldering and the different test methods to access the solderability of components. The first section focused on the theory behind solder and how mathematical analysis can be used to assess solderability when using the force results from the Wetting Balance machine and calculating the Contact Angle. Section two researches the areas of solderability and how one can ensure good solderability is achieved by ensuring the PCB, composition of solder and the ageing has been identified and considered.

There are many international standards that specify the soldering requirements and the ones used in this project are reviewed and compared. It can be seen that the different parameters has varying settings within each of the standards.

The Dip & Look and Wetting Balance Tests are reviewed comprehensively. The Wetting Balance curve explains the different stages when a specimen is been tested in the machine and how the resultant forces and times define how good wetting is.

The MUST II Wetting Balance machine and how it operates is reviewed. Images show how the components are mounted onto the clip for testing and the procedure to be adhered to for ensuring repeatability.

The driving forces such as the three applicable legislations, Waste Electrical and Electronic Equipment (WEEE) focusing on household and industrial appliances, Restriction of certain Hazardous Substances (RoHS) banning the use of six substances (lead (Pb) been one of these) in electrical and electronic equipment and finally End-of-Life Vehicle (ELV) Directive which details the requirements for automobile design taking into consideration the recycling of parts at the end-of-life. The three different alloys being used in this project, SnPb, SAC305 and SN100C, were discussed and also compared to each other in terms of physical, reflow soldering and thermal characteristics.

Finally, the analysis is carried out using Design of Experiment with Minitab. This research will be used thought out each of the chapters by setting up a Design of Experiments to analyse the Dip & Look, and Wetting Balance test methods for a copper wire. Analysis will be done using Main Effect and Interaction plots.

## Chapter 3 Dip & Look Test Evaluation

### 3.0 Introduction

To control production industrial product trials are undertaken to establish a manufacturing process window to ensure the quality of the product and to reduce soldering defects. The majority of soldering defects are attributable to lacking solderability of PCB finish and component terminations. Testing for solderability is necessary. Special solderability requirements are included in any purchase agreement with component and PCB suppliers. [84] From experience, the feedback provided by most component suppliers when responding to a solderability defect, list the Dip & Look test as the means of assessing components solderability. Appendix 1 shows a Quality Problem report from a component supplier using the Dip & Look test.

Process improvement is based on a foundation of engineering analysis and experimentation; one of the recommended tools in this analysis is the use of a Dip & Look solderability test. The variables and factors present in various standards for Dip & Look solderability testing are listed in the Table 3.1.

**Table 3.1 Factors / Variables in Dip & Look Test**

<b>Factors / Variables</b>
Solder bath Temperature
Solder Alloy
PCB/component immersion depth into solder bath
Dwell time of component/PCB in solder
Immersion speed of component/PCB into solder
Component / PCB Weight
Height of Solder in bath
Flux Type
Operator Error

When considering the factors above, it was decided to classify the factors as either ‘Potential Design Factors’ or ‘Controllable Nuisance Factors’. The potential design factors are those that will be varied for the Design of Experiment (DoE) and the controllable nuisance factors are those that may affect the Wettability of the test specimens and must be accounted for, but in the context of this experiment, are not included in the actual Design of Experiments. For example the solder alloy, which is listed as a controllable nuisance factor in Table 3.2, will have an effect on the solderability results of any test specimen but

for the experiment in this chapter, only one alloy is used for each DoE, so therefore its affect remains constant in each DoE. The same applies for Component Weight, Flux Type and Immersion Speed because all three remain constant. Table 3.2 shows the potential design factors and the controllable nuisance factors used in the experiment. These factors were determined from experience working within an electronics manufacturing company, to be either potential design factors or controllable nuisance factors.

**Table 3.2 Potential design factors vs. Nuisance factors**

Potential design factors	Controllable Nuisance factors
Solder bath Temperature	Solder Alloy
Component depth into solder bath	Component Weight
Dwell time of component in solder	Flux Type
Immersion depth in solder	Immersion speed of component into solder

In the context of the Dip & Look experiment, the potential design factors as listed in Table 3.2 will be varied and the controllable nuisance will remain constant.

For the controllable nuisance factors;

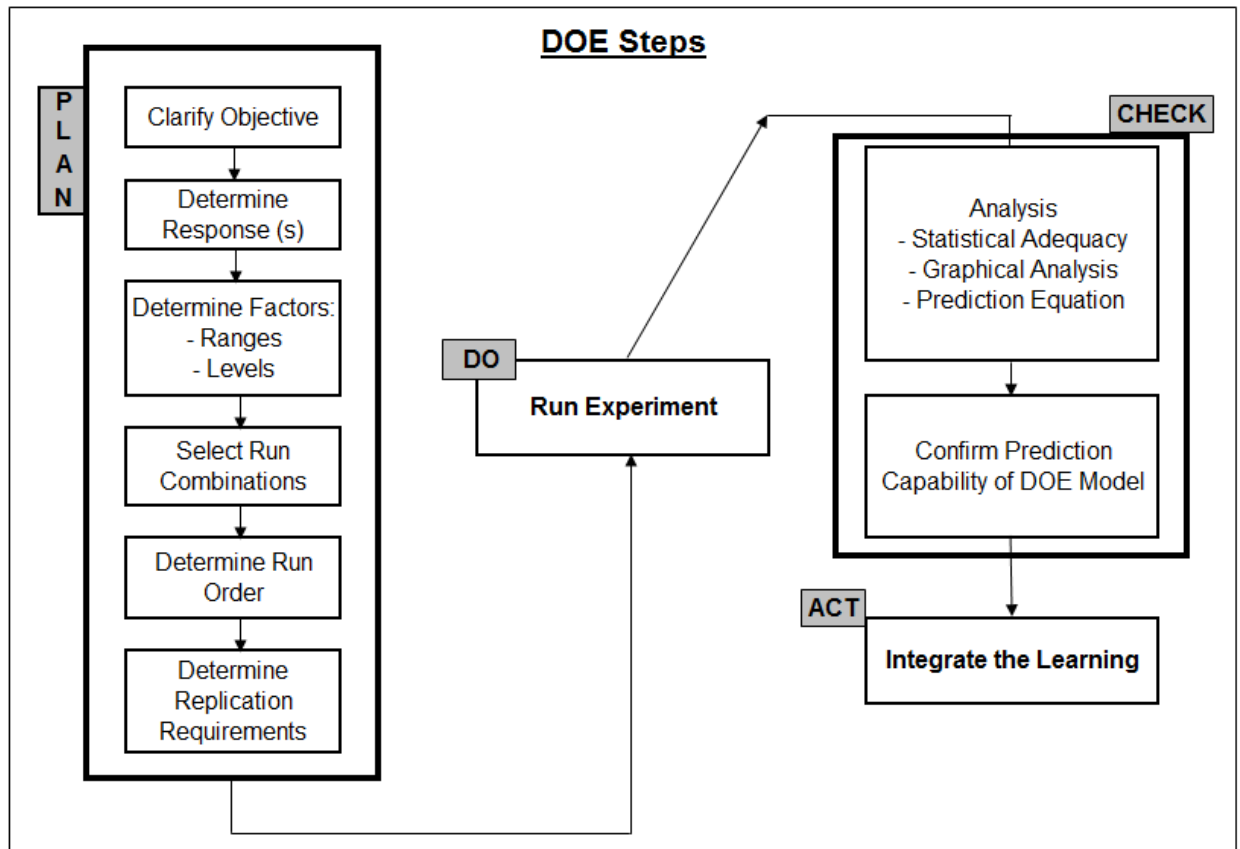
- Solder Alloy was SAC305 and SN100C for lead-free (Pb-Free) and Sn60Pb40 for the lead (Pb) process.
- Component weight was consistent for all alloys, Quad-Flat-Pack (QFP).
- Flux type was Actiec 5 which was the flux provided by the MUST II supplier.
- Immersion Speed was maintained at 15mm/sec. This speed was determined by initial experimentation. Speeds greater than 15mm/sec caused the Wetting Balance machine to go into error mode due to the accuracy of the machine not been capable of stopping at small depths less than 2mm using high speeds. 15mm/sec was optimum.

In order to determine the optimum Dip & Look test settings for PCB's and components in a Pb and Pb-free process, a Design of Experiments method was conducted. The goal of a DoE is as follows:

- A means of determining the settings of the input factors that optimise the response and minimise costs.
- A scientific method for setting tolerances.
- Most effective method for identifying the key input factors.
- Most effective way to gain an understanding of the relationship between the input factors and the response(s).

- A method of building a mathematical model relating the response to the input factors, which is often referred to as process/product characterisation.

The software use to conduct this DoE is Minitab and it was decided to apply Deming's PDCA (Plan-Do-Check-Act) system of process improvement to structure the experiments. This is illustrated in Figure 3.1.



**Figure 3.1 Deming's PDCA Design of Experiments Layout [79]**

### 3.1 Planning Phase

There are various Dip & Look test options available in industry. However there is no clear consensus as to the appropriate combination of tests that defines an acceptable Dip & Look standard at component or PCB level. In order to achieve a workable standard, a review of each available international standard is required to develop a Design of Experiments with a view to obtaining the optimum settings. The main International Standards used for analysis in this project are:

1. J-STD-002C –Solderability Test for Component Leads, Terminations, Lugs, Terminals and Wires.
2. IPC/EIA J-STD-002B – Joint Industry Standard, Solderability Tests for Component Leads, Terminations, Lugs, Terminals and Wires.
3. Department of Defence – MIL-STD-883, Solderability Testing.

4. IPC J-STD-003B – Solderability Tests for Printed Boards.
5. International Standard - CEI IEC 68-2-20, Basis Environmental Testing Procedures, Part 2: Test T, Soldering.
6. IEC68-2-69 – Solderability Testing of electronic components for surface mount technology by the Wetting Balance method.
7. IEC68-2-54 - Solderability Testing of electronic components by the Wetting Balance method.

Table 3.3 summarises the different settings used for each variable within each of the aforementioned standards 1 to 7.

**Table 3.3 Summary of International Standards for Dip & Look test**

<b>International Standards</b>	<b>Solder Temperature (Pb and Pb-Free)</b>	<b>Dwell Time (Seconds)</b>	<b>Immersion Depth (mm)</b>
J-STD-002C	245 $\pm$ 5°C (Pb) 260 $\pm$ 5°C (Pb-free)	5+0/-0.5	1.25mm
J-STD-002B	245 $\pm$ 5°C (Pb)	5+0/-0.5	1.25mm
MIL-STD-883	245 $\pm$ 5°C (Pb)	7+0/-0.5	25.4mm $\pm$ 5mm
IPC J-STD-003B	235 $\pm$ 5°C (Pb) 255 $\pm$ 5°C (Pb-free)	3.0 $\pm$ 0.5	25 $\pm$ 2 mm
IEC 68-2-20	245 $\pm$ 5°C (Pb) 255 $\pm$ 5°C (Pb-free)	5+0/-0.5	10 $\pm$ 2 mm
IEC68-2-69	235 $\pm$ 5°C (Pb) 255 $\pm$ 5°C (Pb-free)	3.0 $\pm$ 0.5	15 $\pm$ 5 mm
IEC68-2-54	235 $\pm$ 3°C (Pb) 255 $\pm$ 3°C (Pb-free)	5+0/-0.5	10 $\pm$ 2 mm

With so many variables within each standard, it was hoped to put procedures in place which would provide not only a repeatable automated test but also a test that had been developed with the company's own component and PCB types in an attempt to reflect the actual soldering processes of Wave and Reflow soldering.

### 3.1.1 Experimental Goals and Scope

The goal of this experiment is to determine the critical variables and any interactions present during the automated Dip & Look solderability testing of components and PCB's. The resulting settings from the DoE should provide a Dip & Look test that would detect any form of contamination on the component termination or PCB surface finish that could

affect wettability. The experiment involved components (Quad Flat Pack's (QFP)) and PCB finishes (HASL SnPb, NiAu, and HASL Pb-free) and was conducted using the MUST II solderability test machine.

### **3.1.2 Responses**

The most critical output response is the percentage of Wettability on the component termination or the PCB pad. These were visually inspected using a microscope at up to 40x magnification; with a target of 95% solder coverage on the termination of the component or the surface of the PCB pads. In the event of achieving solder coverage below the 95% threshold, this would be deemed a failure. Figure 3.3 shows an example of a QFP lead soldered above the 95% coverage area.

### **3.1.3 Factors and Run Combination**

Appendix 2 shows the factors and parameters used in the experiment for both lead and lead-free wave and reflow soldering of components and PCB's using the Dip & Look method. These factors were determined by reviewing the international standards as stated in Section 3.1. From speaking with some component manufacturers, the main factors of the Dip & Look test are solder temperature, immersion speed, immersion depth and dwell time. As stated earlier the immersion speed of 15mm/sec was kept constant throughout the experiment due to the small immersion depths use for the experiment. The number of factors for both PCB's and components were 3, resulting in 27 runs for each process, lead (Pb) and lead-free.

Each factor was assigned a column in the array as shown in Appendix 2. A minimum, medium and maximum level was set for each factor. At the beginning of every run, the machine settings were made with reference to the arrays in Appendix 2. Once steady state conditions were achieved and settings verified, the run was initiated. Each run consisted of one component lead or one PCB finish depending on the test. After the test was completed, each specimen was visually inspected using a microscope for the 95% threshold level and results were recorded as per "Response: Wettability (%)" column in Appendix 2.1, 2.2, 2.3, 2.4, 2.5 and 2.6. Tables 3.4 and 3.5 show the factors used for Wave and Reflow processes using components and PCB's in a lead (Pb) and lead-free process for the Dip & Look D.O.E. As can be seen from Tables 3.4 and 3.5, the solder temperature was the only setting difference for a lead (Pb) and lead-free process.

**Table 3.4 Wave/Reflow settings for Components in a Pb and Pb-free Process**

Factor Name for Components	Min Value	Medium Value	Max Value
Wave Solder Temperature (Pb)	235°C	240°C	245°C
Wave Solder Temperature (Pb-free)	240°C	250°C	260°C
Reflow Solder Temperature (Pb)	210°C	215°C	220°C
Reflow Solder Temperature (Pb-free)	240°C	245°C	250°C
Immersion Time (Pb and Pb-free))	4sec	5sec	6sec
Immersion Depth (Pb and Pb-free)	0.1mm	0.8mm	1.4mm

**Table 3.5 Wave/Reflow settings for PCB's in a Pb and Pb-free Process**

Factor Name for PCB's	Min Value	Medium Value	Max Value
Wave Solder Temperature (Pb)	230°C	235°C	240°C
Wave Solder Temperature (Pb-free)	250°C	255°C	260°C
Immersion Time (Pb and Pb-free)	4sec	5sec	6sec
Immersion Depth (Pb and Pb-free)	0.4mm	0.8mm	1.2mm

### 3.2 Analysis of Results

The solder coverage was entered as a percentage into the DoE software (Minitab) for analysis. As each run gave the required 95% solder coverage on the component lead, it was concluded without using Minitab, that no factor had any significant effect on the wettability for a Dip & Look test. The only explanation for these results at this stage of the project was to conclude that the Dip & Look test was a forgiving test and would require further investigation to prove whether or not it was a reliable means of testing the wettability of a component termination or the PCB finish.

It was decided to take the medium settings of Tables 3.4 and 3.5 above and run a series of Dip & Look tests on a samples range of components and PCB's to determine if any failures would result. These settings can be seen in Tables 3.6, and 3.7.

**Table 3.6 Summary of Dip & Look settings for Components**

Reflow Process	Pb	Pb-free
Solder Temperature	215 ±1°C	245 ±1°C
Immersion Time	4 seconds	4 seconds
Immersion Depth	0.8mm	0.8mm

**Table 3.7 Summary of Dip & Look settings for Components and PCB's**

<b>Wave Process - Components</b>	<b>Pb</b>	<b>Pb-free</b>
Solder Temperature	240±1°C	250±1°C
Immersion Time	5 seconds	5 seconds
Immersion Depth	0.8mm	0.8mm
<b>Wave Process – PCB's</b>	<b>Pb</b>	<b>Pb-free</b>
Solder Temperature	235 ±1°C	255 ±1°C
Immersion Time	4 seconds	4 seconds
Immersion Depth	0.8mm	0.8mm

### 3.2.1 Further Analysis of DoE Settings for Dip & Look Test

In order to test the validity of the settings in Tables 3.6 and 3.7 a wide range of components from resistors to large electrolytic caps were tested. The sequence of the testing was a repeat of the testing initially used to determine the medium DoE settings. Again each component reached the 95% target for solder coverage.

The rework database, which stores a history of soldering defects in series production, was reviewed to determine the components that had a history of soldering issues within the company. These components were again tested and all passed the 95% solder coverage. At this stage of the investigation it was concluded that the resulting DoE settings did not provide a valid test as all components were passing.

To try to achieve settings that resulted in a failure (less than 95%), it was decided to reduce the temperature of the solder in increments of 5°C and keep all other settings constant. The reason for varying temperature was due to the fact that temperature is one of the main factors in forming a solder joint along with flux and base metal [28].

The results showed for:

- a) Pb-free process (SAC305) - Wave/Reflow for components and PCB's;
  - The temperature reached 225°C before results of less than 95% solder coverage were achieved on the 144pin 0.5mm pitch QFP. As 221°C is the liquidus point of SAC alloy solder the result was again expected at this point because the low temperature of the solder.





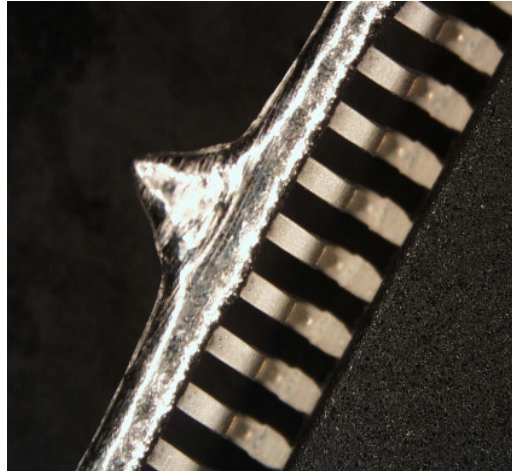
**Figure 3.2 QFP leads with SAC305 solder not wetting at 221°C [42]**

- b) Pb-free process (SN100C) - Wave/Reflow for components and PCB's;
- The temperature reached 225°C before results of less than 95% solder coverage were achieved. As 227°C is the liquidus point of SN100C alloy solder the result was again expected at this point because the low temperature of the solder.



**Figure 3.3 QFP leads with SN100C solder not wetting at 227°C [42]**

- a) Pb process – Wave/Reflow for components and PCB's;
- The temperature reached 185°C before results of less than 95% solder coverage were achieved. As 183°C is the liquidus point of Sn/Pb solder the result was expected at this point. An example of the failure can be seen in Figure 3.4 below, solder does not wet to the leads resulting in a failure because the low temperature of the solder.



**Figure 3.4 QFP leads with Pb solder not wetting at 183°C [42]**

Given the results above, it could be concluded that Dip & Look testing in a Pb and Pb-free environment does not effectively scrutinise the solderable properties of components and PCB's to an extent that contamination on the surface of the termination or pad would be detected.

Some international standards use a preconditioning test on the components and PCB's before the Dip & Look test. The preconditioning test acts as a means of aging and oxidising components or PCBs. A preconditioning of the component or PCB's surface would need to be investigated to determine if any failures would result by using the same DoE settings as per Tables 3.6 and 3.7. This is discussed in Section 3.3.

### **3.3 XRF and Pre-Conditioning Testing: Dry Bake and Steam**

Due to the fact that some components and PCB's are not used immediately after purchase, the storage was an area to be included in Dip & Look testing which would factor in aging. The ideal preconditioning test would age the surface to be tested and impose restrictive conditions of weak flux, standard temperature, and adequate time. XRF (X-RAY Fluorescence) was used to check the plating thickness of the components in order ascertain if it was uniform between all components. The results showed a significant variation of tin-plating thickness, see Figure 3.5.

Ten components were measured using a Helmut Fischer XRF machine. The same corner lead on each of the ten components was measured. The reason for measuring this component was because of the history of solderability issues on this particular lead. The range of tin-plating thickness measurements was 8.33µm, minimum measurement 4.37µm and maximum measurement 12.7µm. With such a range of values for tin-plating thickness, the components were then pre-conditioned.

**HELMUT FISCHER GmbH + Co. KG**

Industriestrasse 21  
71069 Sindelfingen

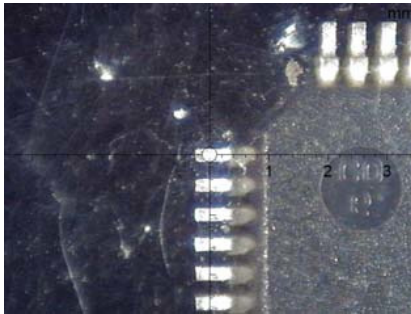
**Fischerscope® XRAY XAN**

Product: 5 / Sn / Cu Leads

Dir.: Kostal Block:

299

Application: 1 / Sn + Ni / Cu Leads



n=	1	Sn 1 =	8.19 $\mu\text{m}$
n=	2	Sn 1 =	4.37 $\mu\text{m}$
n=	3	Sn 1 =	6.13 $\mu\text{m}$
n=	4	Sn 1 =	12.7 $\mu\text{m}$
n=	5	Sn 1 =	9.8 $\mu\text{m}$
n=	6	Sn 1 =	11.4 $\mu\text{m}$
n=	7	Sn 1 =	5.55 $\mu\text{m}$
n=	8	Sn 1 =	6.68 $\mu\text{m}$
n=	9	Sn 1 =	11.14 $\mu\text{m}$
n=	10	Sn 1 =	7.58 $\mu\text{m}$

	Sn 1
Mean	8.35 $\mu\text{m}$
Range	8.33 $\mu\text{m}$
Number of readings	10
Min. reading	4.37 $\mu\text{m}$
Max. reading	12.7 $\mu\text{m}$
Measuring time	40 sec
Operator:	BW QFP lead

**Figure 3.5 XRF Plating Thickness Measurements**

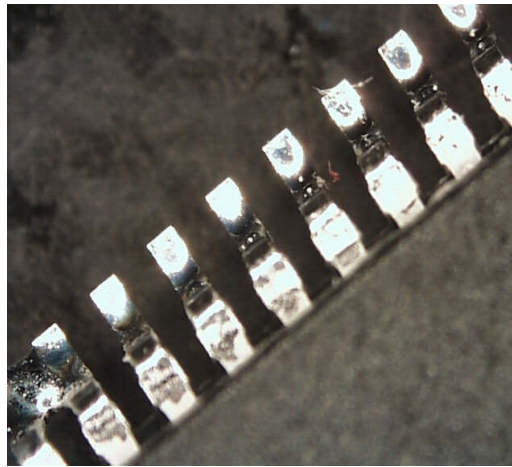
### 3.3.1 Components

After reviewing the IPC standards mentioned in Section 3.1.1 there are two preconditioning tests used for components:

1. Dry bake
2. Steam test.

The exposure time for the Dry bake preconditioning test was 16 hours  $\pm$ 30 minutes at a constant temperature of 150°C and for the Steam preconditioning test the oven been used only had the capability of 8 hours at 125°C with 95% relative humidity. [59, 60] The

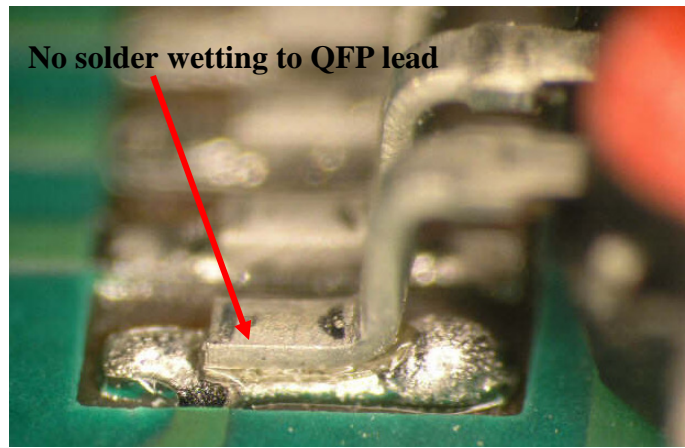
components were exposed to a controlled environment in specialised ovens and the settings were applied for the Dry bake and Steam test. After removing the components from the dry bake oven, the Dip & Look test was started using the MUST II Wetting Balance machine and the same settings previously used in Tables 3.6 and 3.7. Again each component was tested and visually inspected for the 95% solder coverage. It is now concluded that using the Dry Bake preconditioning test before Dip & Look solderability testing did not affect the results for 95% solder coverage, Figure 3.6. Similar to the Dry Bake preconditioning test, the component that had been subjected to a controlled environment Steam test were ran using the same DoE settings.



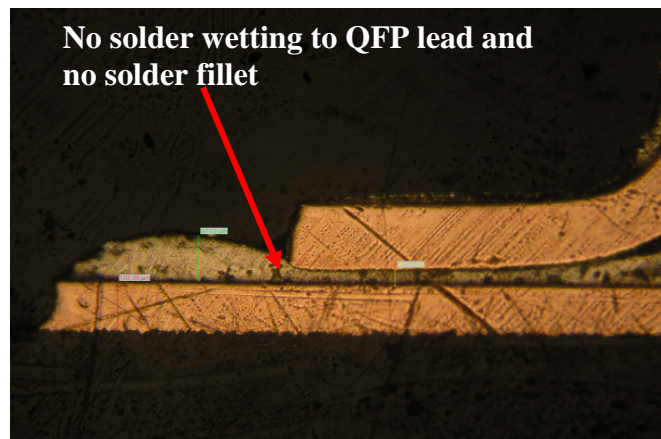
**Figure 3.6 QFP leads with solder [42]**

Again the results showed that all components passed the 95% solder coverage level. It was concluded that the Steam precondition test did not have any effect on the components performance while using the Dip & Look solderability test.

The results showed that all components passed the 95% solder coverage when using the Dip & Look test. In order to assess the performance of the same preconditioned components on a series production line, a sample of components were automatically placed onto a PCB and soldered using a Reflow process with Nitrogen. The QFP leads were inspected using a high magnification microscope and also cross-sectioned to assess the solder joint fillet. Figure 3.7 shows a High Magnification Microscope image of solder not wetting to the leads and Figure 3.8 is an X-Ray image of the same component lead after cross sectioning.



**Figure 3.7 High Magnification Microscope Image of QFP leads [42]**



**Figure 3.8 Cross Section of QFP lead [42]**

It is evident from the images in Figures 3.7 and 3.8 that these components had solderability issues even though the Dip & Look test had passed all these components for use in a production line. Even with pre-conditioning of the components, which is a means of ageing and oxidising, and also the variation of plating thickness on the leads, the Dip & Look test passed these poor solderability components and the failures were evident in series production using nitrogen reflow soldering. There is now evidence from this chapter, to state that the Dip & Look solderability test is not a reliable test to detect any form of poor solderability and should be removed as a means of assessing a component or PCB's soldering ability.

### **3.4 Summary and Conclusion**

This aim of this chapter was to determine and investigate using Deming's PDCA (Plan-Do-Check-Act) and Minitab, a suitable set of parameters for Dip & Look solderability testing using the MUST II solderability tester with SnPb, SAC305, and SN100C alloys. The reason for using the MUST II solderability tester was to rule out operator error by

automating the testing. The component or PCB could be loaded onto the clip of the Wetting Balance machine and all movement too and from the solder would be automated.

- The settings for Dip & Look testing vary from standard to standard and for some companies, component and PCB suppliers; can use different settings to suit their manufacturing process.
- The results of the Design of Experiments show that all components and PCB's tested using the arrays in Appendix 2, achieve the 95% solder coverage without any preconditioning. It was also determined that even with preconditioning, a sequence that ages the test specimens, the 95% solder coverage was easily achieved.
- XRF measurements highlighted the variation of tin-plating thickness on leads between ten components.
- In order to assess the performance of the same preconditioned components on a series production line, a sample of components were automatically placed onto a PCB and soldered using nitrogen reflow process. It was evident that there were solderability issues with these components when used on a series production line even though the Dip & Look test has passed them for use.
- It can be concluded that the Dip & Look test method is a very forgiving test. Even the most extreme contaminated surfaces passed the 95% solderability coverage of the Dip & Look test.
- One must also question the inspection criteria for the Dip & Look test, a minimum of 95% solder coverage on the area to be tested. A visual inspection by an operator determines the 95% coverage, which in its self can be difficult to ascertain. If soldering onto a HASL finish PCB or termination the difficulty trying to determine which is the solder and which is the PCB or termination finish is another area of concern because of the visual similarity. This inspection criteria requirement is not conclusive enough and can leave the result subject to a lot of questions by the PCB and component users and the suppliers.
- Like most of the supplier quality documentations supplied by the component and PCB suppliers, the Dip & Look test is been used throughout the world to assess the soldering quality. With positive results from this supplier testing it will be very difficult to convince suppliers of the requirement to move away from Dip & Look.
- The Dip & Look test is no longer considered as a viable and reliable solderability test and all suppliers of components and PCBs should be requested to review their solderability test criteria.

The Wetting Balance method is theoretically based as it tests for wetting time and wetting force – two important factors not investigated when using the Dip & Look method. For this reason an in-depth investigation into the Wetting Balance test will be done in the next chapters to try and determine the significant factors and their effect on each of the responses, time to buoyancy, time to reach the zero line, maximum force, time to reach maximum force, force after 2 seconds and force after five seconds. Component and PCB suppliers will be required to use the Wetting Balance test and the determined settings for assessing solderability. This will improve the overall quality of PCB's and components and reduce scrap costs.



## Chapter 4 Repeatability Study on Wetting Balance Machine

### 4.0 Introduction

Prior to conducting any experiments on the MUST II Wetting Balance machine, an in-depth repeatability study was required in order to assess the machine's performance paying particular attention to its ability to provide accurate and repeatable results, while gaining a complete understanding of the machine's operation. It was also vitally important to understand and minimise, as much as possible, any external influences other than the machine operation, which may affect the accuracy of the results. This chapter will assess the repeatability of the MUST II Wetting Balance machine that is used throughout this project. The manufacturer of the MUST II recommends the use of a Gauge R&R (Repeatability and Reproducibility) study on the machine to assess its repeatability. This method was not used in this project because the same operator performs all testing throughout the project.

The Machine Capability or  $C_{mk}$  is another means of assessing a machine capability. For  $C_{mk}$  the required value is  $\geq 1.33$  [80] as discussed in Section 2.9.7 of the Literature Review. Along with assessing the machine capability, the repeatability of the machine is determined with the use of X-bar charts and R-charts. Both charts are used in detail to assess the stability of the process.

A systematic examination of the MUST II Wetting Balance machine would ensure that the quality features and characteristics required could be investigated under statistically controlled conditions. The supplier of the MUST II Wetting Balance machine carried out the necessary annual calibration on the 27th of July 2012 and the machine was certified for use. A copy of this calibration certificate is available in Appendix 3. The calibration involved the following:

1. Force measurement calibration of the component clip holder – Verified the deviation of the force measured by the holder is within the IEC68-2-54 standard of  $<5\%$ .
2. Temperature calibration of the solder bath – Verified the deviation of solder temperature of the bath or globule is within the IEC68-2-54 standard of  $\pm 3^{\circ}\text{C}$ .
3. Immersion Depth of the component lead in the solder – Meets the requirements of the IEC68-2-54 standard, maximum error of  $\pm 0.2\text{mm}$ .
4. Immersion Speed of the component lead in the solder – Meets the requirements of the IEC68-2-54 standard, maximum error of  $\pm 1\text{mm/sec}$ .



5. Dwell Time of the component lead in the solder – Meets the requirements of the IEC68-2-54 standard, shall be adjusted from 0 to 10 seconds.

The above calibration checks ensured that the machine operation for the variables used in the study; force, temperature, immersion depth, immersion speed and dwell time were all measuring within the desired requirements of the International Standard IEC68-2-54. Since the force measurements are in milli-newtons (mN), the variation for all the aforementioned variables is required to be to an absolute minimum in order to achieve reliable, consistent and accurate results.

The Six Sigma philosophy, Define-Measure-Analyse-Improve-Control or DMAIC, was used to provide a framework for assessing the Wetting Balance machines repeatability.

## **4.1 Define Phase**

The main goals of this investigation were:

- Determine the repeatability of the MUST II Wetting Balance machine by using the time to reach buoyancy ( $T_a$ ) and the time to reach the zero line ( $T_b$ ). The internationally recognised requirement for  $T_a$  is to reach the buoyancy line in less than 0.6seconds and for  $T_b$ , to reach the zero line in less than 1 second. A force measurement such as  $F_{max}$  was also initially considered but due to the fact that there are no recognised international acceptance criteria it was omitted. As stated in Chapter 1, one of the objectives of this project is to develop model equations that can be used to predict responses including  $F_{max}$  value.
- Assess the Wetting Balance machine ability to provide accurate and consistent results.
- Eliminate and reduce as much as possible any external influences which may affect the results.

## **4.2 Measure Phase**

The repeatability study was conducted on the current MUST II Wetting Balance machines performance using a 0.9mm copper wire. In total fifty repeated tests were measured using the settings in Table 4.1. The following procedure was carried out to determine the machine's repeatability:

- A length of 20mm copper wire of 0.9mm diameter was used. The reason for using a copper wire instead of component leads was to minimise any variation of the component leads ability to solder as a result of poor component storage and shelf life. An investigation was carried out to determine the optimum length of copper

wire between a 20mm and 40mm length. The results were far more stable with a 20mm length of copper wire because of the heat conduction with copper. For each of the fifty measurements 20mm lengths of copper wires were used.

- The solder used in the bath was SN100C, an alloy used throughout the industry for soldering electronic components.
- The flux used for the test was SLC60, the qualified production flux used within many electronics manufacturing companies.
- The settings in Table 4.1 were entered into the Wetting Balance machine. The Wetting Balance machine manufacturer recommended these settings based on their evaluations and experience.

**Table 4.1 Wetting Balance settings used for Repeatability Analysis**

Variable	Settings
Immersion Speed	20mm/sec
Immersion Depth	4mm
Dwell Time	5 seconds
Solder Temperature	260°C

- Using gloves, the 20mm length of copper wire was mounted onto the Wetting Balance holder-using clip no. 18.
- The program was enabled and each step was automatically prompted by the machine, flux applied and dross removed from solder bath surface.

Each result was automatically recorded by the machine and presented in a graphical format. The software on the Wetting Balance machine was only capable of recording fifteen measurements on one graph so the above procedure was repeated until the fifty measurements were complete. Figure 4.1 is an example of a MUST II graph and all results are listed in Appendix 4.

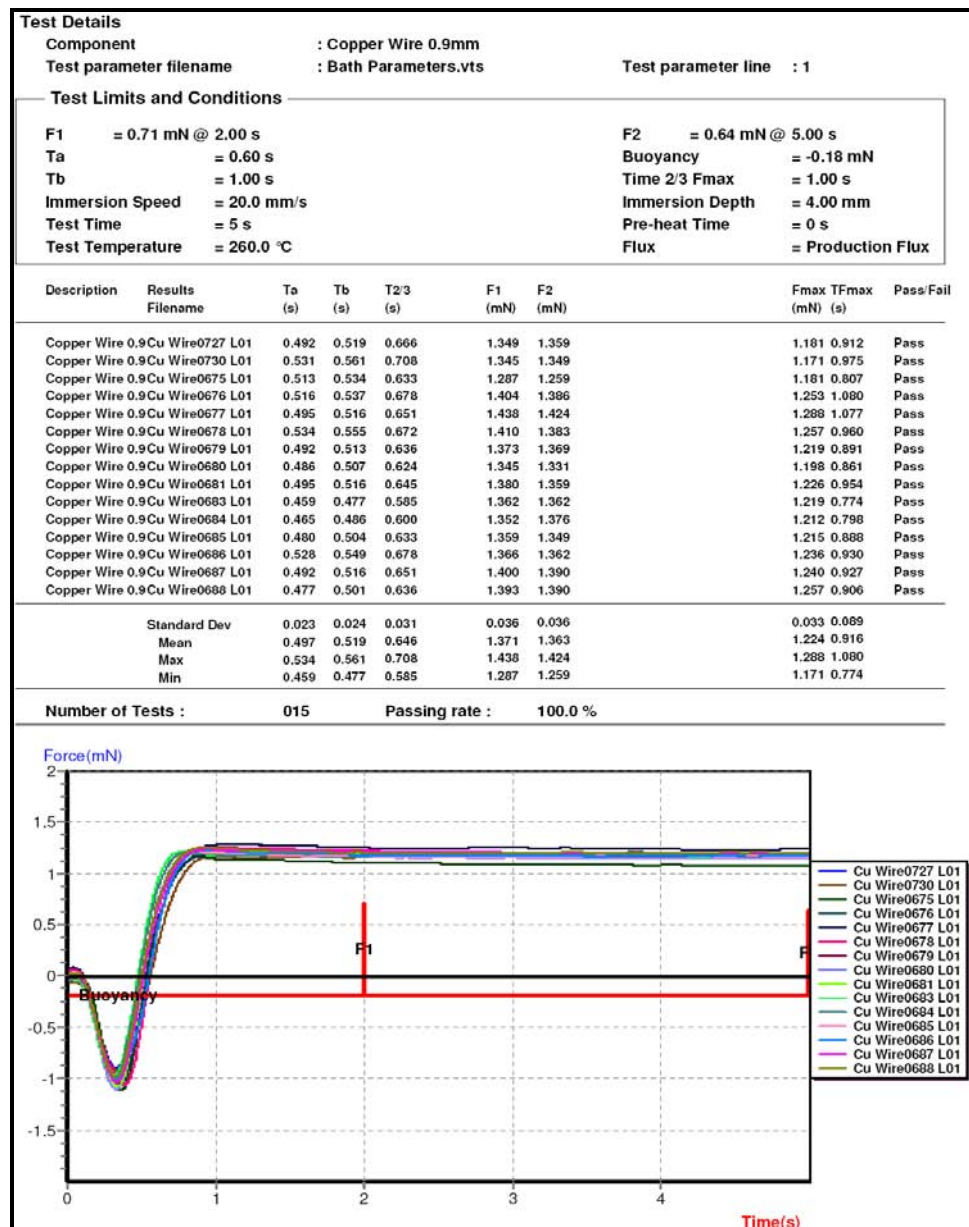


Figure 4.1 MUST II Wetting Balance Graph

### 4.2.1 Results

The fifty-recorded results using the settings in Table 3.1 for the responses;

- Ta – time to reach the buoyancy line, which is < 0.6 seconds as stated in the International Standards.
- Tb - time to reach the zero line, which is < 1 second as per the international standards.

were analysed using the X-Bar and R-Charts.

### 4.3 Analyse Phase

An analysis of the time to buoyancy (Ta) and the time to reach the zero line (Tb) were analysed in order to determine the machine repeatability.

### 4.3.1 Ta, Time to buoyancy

An X-Bar and R-Chart were developed for fifty-readings of Ta using the 0.9mm diameter copper wire, see Figure 4.2 and Figure 4.3. To construct X-Bar and R-Charts the data from the MUST II was analysed using the calculations in Equations 4.1, 4.2, 4.3 and 4.4. From these calculations UCL (Upper Control Limits) and LCL (Lower Control Limits) for X-Bar and R-Charts were determined and these are represented in Table 4.2. There are currently no specification UCL or LCL limits for Ta. The International Standards state the solder must wet to the test specimen in  $< 0.6$  seconds. One must not confuse this specification requirement with LCL and UCL for any Control charts.

#### X-Bar Control Chart Calculations:

$$UCL = \bar{X} + (A_2 * \bar{R}) \dots \text{Eq. 4.1}$$

$$LCL = \bar{X} - (A_2 * \bar{R}) \dots \text{Eq. 4.2}$$

$$UCL = 0.499 + (1.88 * 0.032)$$

$$LCL = 0.499 - (1.88 * 0.032)$$

$$UCL = 0.558$$

$$LCL = 0.439$$

#### R-Chart Calculations:

$$UCL = D_4 * \bar{R} \dots \text{Eq. 4.3}$$

$$LCL = D_3 * \bar{R} \dots \text{Eq. 4.4}$$

$$UCL = 3.267 * 0.032$$

$$LCL = 0 * 0.032$$

$$UCL = 0.104$$

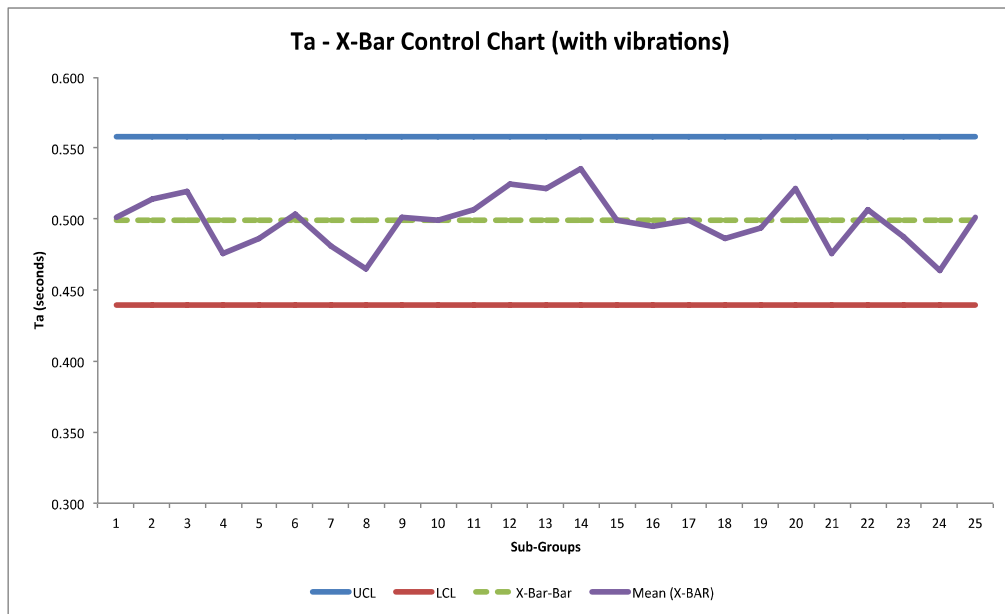
$$LCL = 0$$

**Table 4.2 Ta Results – X-Bar and R-Charts**

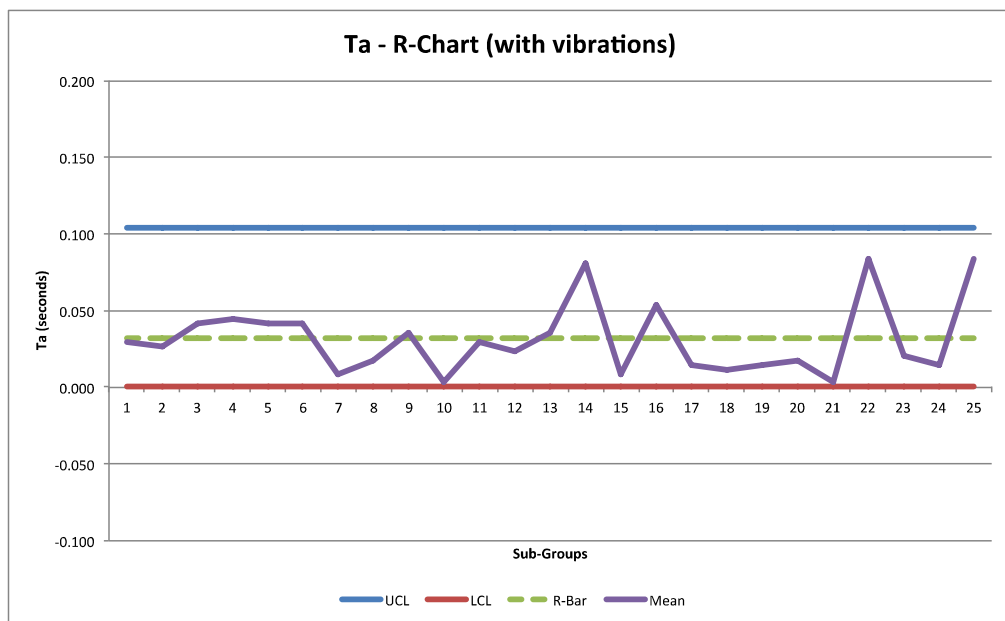
No.	Ta Results from MUST II		Mean (X-BAR)	Max	Min	Range	X-BAR Control CHART			R-Control Chart		
							UCL	LCL	Mean (X-BAR)	UCL	LCL	Mean
1	0.516	0.486	0.501	0.516	0.486	0.030	0.558	0.439	0.501	0.104	0.000	0.030
2	0.528	0.501	0.514	0.528	0.501	0.027	0.558	0.439	0.514	0.104	0.000	0.027
3	0.540	0.498	0.519	0.540	0.498	0.042	0.558	0.439	0.519	0.104	0.000	0.042
4	0.453	0.498	0.476	0.498	0.453	0.045	0.558	0.439	0.476	0.104	0.000	0.045
5	0.465	0.507	0.486	0.507	0.465	0.042	0.558	0.439	0.486	0.104	0.000	0.042
6	0.483	0.525	0.504	0.525	0.483	0.042	0.558	0.439	0.504	0.104	0.000	0.042
7	0.477	0.486	0.481	0.486	0.477	0.009	0.558	0.439	0.481	0.104	0.000	0.009
8	0.456	0.474	0.465	0.474	0.456	0.018	0.558	0.439	0.465	0.104	0.000	0.018
9	0.483	0.519	0.501	0.519	0.483	0.036	0.558	0.439	0.501	0.104	0.000	0.036
10	0.498	0.501	0.499	0.501	0.498	0.003	0.558	0.439	0.499	0.104	0.000	0.003
11	0.492	0.522	0.507	0.522	0.492	0.030	0.558	0.439	0.507	0.104	0.000	0.030
12	0.537	0.513	0.525	0.537	0.513	0.024	0.558	0.439	0.525	0.104	0.000	0.024
13	0.504	0.540	0.522	0.540	0.504	0.036	0.558	0.439	0.522	0.104	0.000	0.036
14	0.495	0.576	0.535	0.576	0.495	0.081	0.558	0.439	0.535	0.104	0.000	0.081
15	0.504	0.495	0.500	0.504	0.495	0.009	0.558	0.439	0.500	0.104	0.000	0.009
16	0.522	0.468	0.495	0.522	0.468	0.054	0.558	0.439	0.495	0.104	0.000	0.054
17	0.507	0.492	0.500	0.507	0.492	0.015	0.558	0.439	0.500	0.104	0.000	0.015
18	0.480	0.492	0.486	0.492	0.480	0.012	0.558	0.439	0.486	0.104	0.000	0.012
19	0.501	0.486	0.493	0.501	0.486	0.015	0.558	0.439	0.493	0.104	0.000	0.015
20	0.513	0.531	0.522	0.531	0.513	0.018	0.558	0.439	0.522	0.104	0.000	0.018
21	0.477	0.474	0.476	0.477	0.474	0.003	0.558	0.439	0.476	0.104	0.000	0.003
22	0.549	0.465	0.507	0.549	0.465	0.084	0.558	0.439	0.507	0.104	0.000	0.084
23	0.477	0.498	0.487	0.498	0.477	0.021	0.558	0.439	0.487	0.104	0.000	0.021
24	0.471	0.456	0.464	0.471	0.456	0.015	0.558	0.439	0.464	0.104	0.000	0.015
25	0.543	0.459	0.501	0.543	0.459	0.084	0.558	0.439	0.501	0.104	0.000	0.084
Sum of Mean (X-BAR)			12.467	Sum of Range			0.795					
X-BAR-BAR			0.499	R-BAR			0.032					

It is evident from both charts in Figures 4.2 and 4.3 that the Wetting Balance test using the MUST II machine ensures a stable process. All results from the 50 readings are within the

calculated UCL and LCL and it can be concluded that the machine repeatability is stable based on these results.



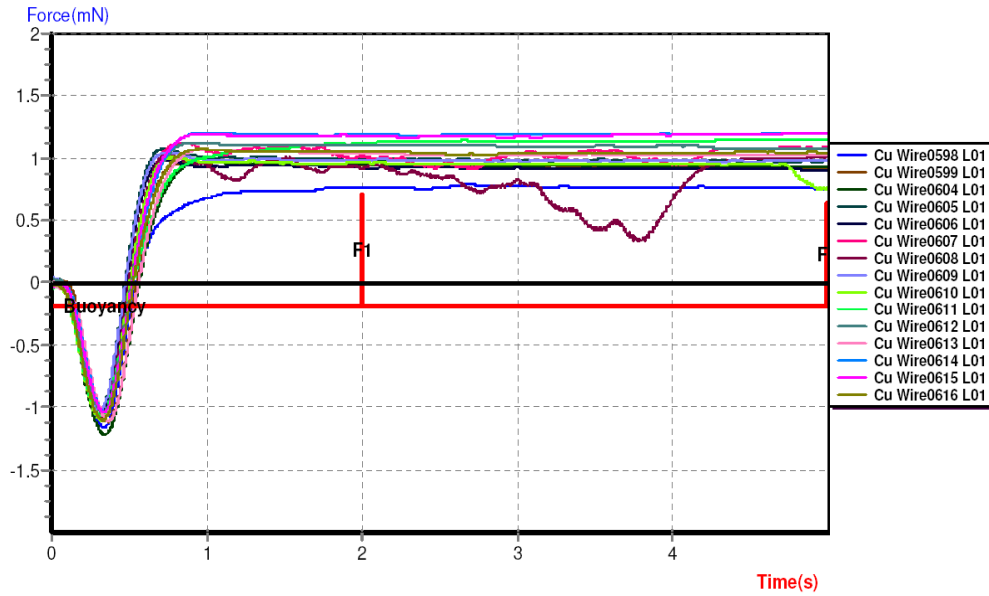
**Figure 4.2 X-Bar Control Chart for Ta**



**Figure 4.3 R-Bar Chart for Ta**

However, it was noted at this point that the graphical representations of the fifty readings did not give a high level of confidence. Figure 4.4 is a snapshot from a graph for fifteen readings of the fifty measurements taken. It can be seen that there are unstable graph lines in Figure 4.4 and the instability of these lines can have a major impact on the results. It was evident at this point that there were some unknown influences causing this instability

whether it was a) the machine's performance, or b) some external factors affecting the machines performance.



**Figure 4.4 Fifteen readings from the fifty measurements**

In order to ascertain further information about this instability, the machines repeatability in terms of Tb was investigated using the same fifty measurement readings.

#### 4.3.2 Time to reach Zero line, Tb

The globally recognised specification stated within International Standards is < 1 second for Tb. Again X-Bar and R-Charts are used to assess repeatability using the 50 readings for Tb. The calculations for UCL and LCL were as follows:

##### X-Bar Control Chart Calculations:

$$UCL = \bar{X} + (A_2 * \bar{R}) \dots \text{Eq. 4.1}$$

$$LCL = \bar{X} - (A_2 * \bar{R}) \dots \text{Eq. 4.2}$$

4.2

$$UCL = 0.523 + (1.88 * 0.032)$$

$$LCL = 0.523 - (1.88 * 0.032)$$

$$UCL = \underline{0.584}$$

$$LCL = \underline{0.463}$$

##### R-Chart Calculations:

$$UCL = D_4 * \bar{R} \dots \text{Eq. 4.3}$$

$$LCL = D_3 * \bar{R} \dots \text{Eq. 4.4}$$

$$UCL = 3.267 * 0.032$$

$$LCL = 0 * 0.032$$

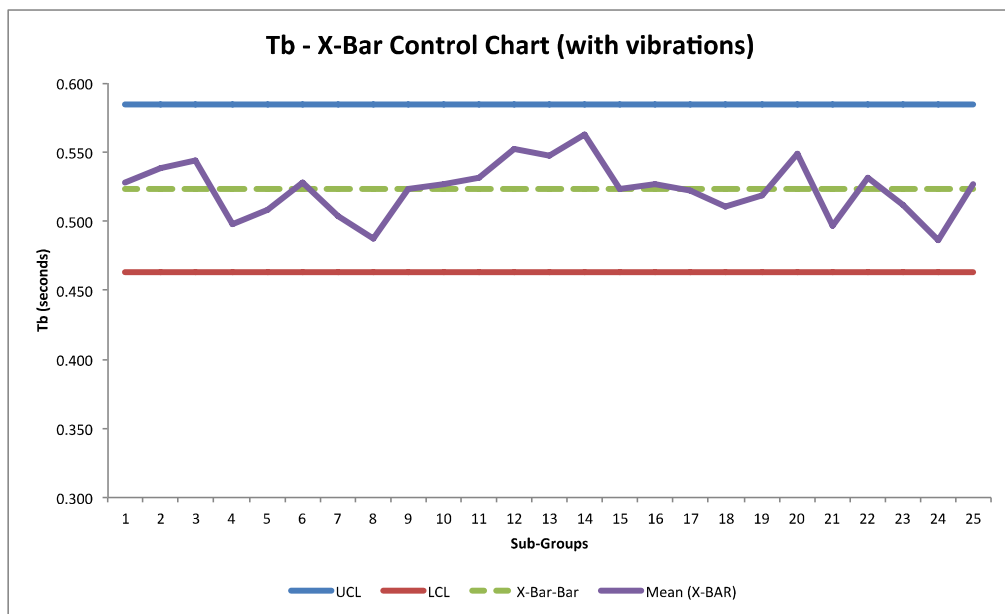
$$UCL = \underline{0.105}$$

$$LCL = \underline{0}$$

Table 4.3 shows the Tb results for the 50 readings with the UCL and LCL limits from the calculations in Equations 4.1, 4.2, 4.3 and 4.4.

**Table 4.3 Tb Results – X-Bar and R-Charts**

No.	Tb Results from MUST II		Mean (X-BAR)	Max	Min	Range	X-BAR Control CHART				R-Control Chart			
							UCL	LCL	X-Bar-Bar	Mean (X-BAR)	UCL	LCL	R-Bar	Mean
1	0.546	0.510	0.528	0.546	0.510	0.036	0.584	0.463	0.523	0.528	0.105	0	0.032	0.036
2	0.549	0.528	0.539	0.549	0.528	0.021	0.584	0.463	0.523	0.539	0.105	0	0.032	0.021
3	0.567	0.522	0.545	0.567	0.522	0.045	0.584	0.463	0.523	0.545	0.105	0	0.032	0.045
4	0.474	0.522	0.498	0.522	0.474	0.048	0.584	0.463	0.523	0.498	0.105	0	0.032	0.048
5	0.486	0.531	0.509	0.531	0.486	0.045	0.584	0.463	0.523	0.509	0.105	0	0.032	0.045
6	0.507	0.549	0.528	0.549	0.507	0.042	0.584	0.463	0.523	0.528	0.105	0	0.032	0.042
7	0.498	0.510	0.504	0.510	0.498	0.012	0.584	0.463	0.523	0.504	0.105	0	0.032	0.012
8	0.477	0.498	0.487	0.498	0.477	0.021	0.584	0.463	0.523	0.487	0.105	0	0.032	0.021
9	0.507	0.540	0.524	0.540	0.507	0.033	0.584	0.463	0.523	0.524	0.105	0	0.032	0.033
10	0.528	0.525	0.526	0.528	0.525	0.003	0.584	0.463	0.523	0.526	0.105	0	0.032	0.003
11	0.516	0.546	0.531	0.546	0.516	0.030	0.584	0.463	0.523	0.531	0.105	0	0.032	0.030
12	0.561	0.543	0.552	0.561	0.543	0.018	0.584	0.463	0.523	0.552	0.105	0	0.032	0.018
13	0.528	0.567	0.548	0.567	0.528	0.039	0.584	0.463	0.523	0.548	0.105	0	0.032	0.039
14	0.519	0.606	0.563	0.606	0.519	0.087	0.584	0.463	0.523	0.563	0.105	0	0.032	0.087
15	0.528	0.519	0.523	0.528	0.519	0.009	0.584	0.463	0.523	0.523	0.105	0	0.032	0.009
16	0.549	0.504	0.527	0.549	0.504	0.045	0.584	0.463	0.523	0.527	0.105	0	0.032	0.045
17	0.528	0.516	0.522	0.528	0.516	0.012	0.584	0.463	0.523	0.522	0.105	0	0.032	0.012
18	0.501	0.519	0.510	0.519	0.501	0.018	0.584	0.463	0.523	0.510	0.105	0	0.032	0.018
19	0.525	0.513	0.519	0.525	0.513	0.012	0.584	0.463	0.523	0.519	0.105	0	0.032	0.012
20	0.540	0.558	0.549	0.558	0.540	0.018	0.584	0.463	0.523	0.549	0.105	0	0.032	0.018
21	0.498	0.495	0.497	0.498	0.495	0.003	0.584	0.463	0.523	0.497	0.105	0	0.032	0.003
22	0.573	0.489	0.531	0.573	0.489	0.084	0.584	0.463	0.523	0.531	0.105	0	0.032	0.084
23	0.501	0.522	0.512	0.522	0.501	0.021	0.584	0.463	0.523	0.512	0.105	0	0.032	0.021
24	0.495	0.477	0.486	0.495	0.477	0.018	0.584	0.463	0.523	0.486	0.105	0	0.032	0.018
25	0.570	0.483	0.527	0.570	0.483	0.087	0.584	0.463	0.523	0.527	0.105	0	0.032	0.087
Sum of Mean (X-BAR)			13.082	Sum of Range			0.807							
X-BAR-BAR			0.523	R-BAR			0.032							

**Figure 4.5 X-Bar Control Chart for Tb**

Again similar to Ta, the results from the X-Bar and R-Charts show a stable process. However, the Tb response does not provide any further information regarding the unstable lines on the graphs because the unstable peaks occur after 1 second into the test. For this reason F1 and F2 forces were analysed.

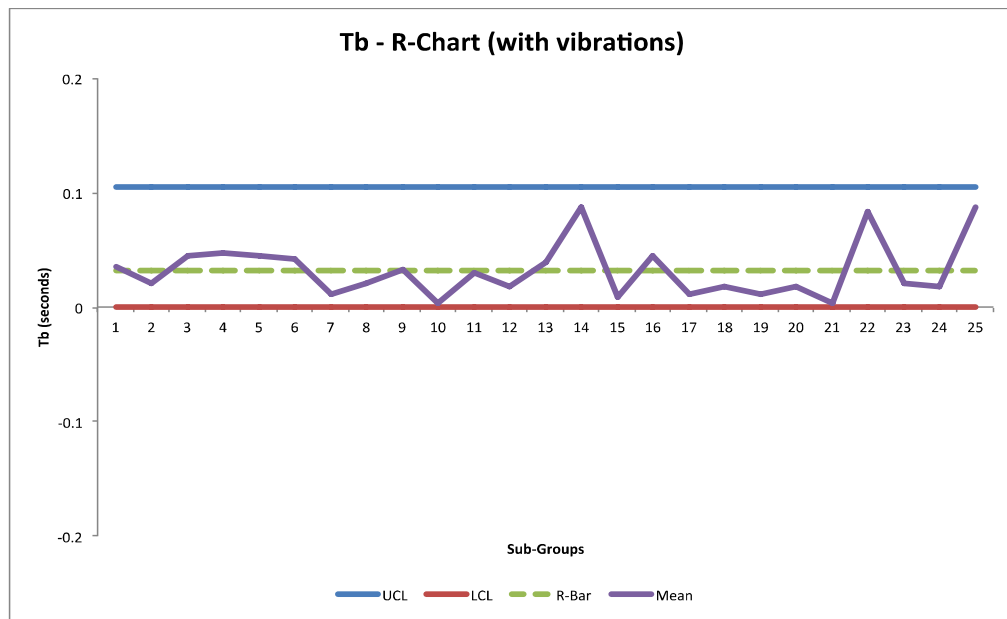


Figure 4.6 R-Bar Chart for Tb

### 4.3.3 F1 and F2

In order to ascertain the root cause of the instability of the graph lines, the standard deviation was calculated by Minitab to be, F1 - 0.127210 and F2 - 0.129410, which indicated good repeatability of force measurement from two to five seconds by the MUST II machine.

Table 4.4 F1 and F2 Results

No.	F1	F2	Difference F1 & F2
1	0.949	0.935	0.014
2	1.128	1.094	0.034
3	1.135	1.111	0.024
4	1.176	1.163	0.014
5	1.104	1.090	0.014
6	1.204	1.273	0.069
7	1.104	1.190	0.086
8	1.169	1.163	0.007
9	1.149	0.942	0.207
10	1.307	1.335	0.028
11	1.287	1.269	0.017
12	1.225	1.214	0.010
13	1.373	1.383	0.010
14	1.366	1.383	0.017
15	1.242	1.228	0.014
16	1.242	1.238	0.003
17	1.400	1.152	0.248
18	1.369	1.355	0.014
19	1.417	1.431	0.014
20	1.359	1.362	0.003
21	1.349	1.359	0.010
22	1.328	1.345	0.017
23	1.366	1.369	0.003
24	1.345	1.355	0.010
25	1.410	1.404	0.007
26	1.228	1.214	0.014
27	1.345	1.338	0.007
28	1.407	1.431	0.024
29	1.366	1.362	0.003
30	1.342	1.349	0.007
31	1.424	1.431	0.007
32	1.397	1.245	0.152
33	1.355	1.373	0.017
34	1.362	1.369	0.007
35	1.349	1.349	0.000
36	1.373	1.383	0.010
37	1.366	1.359	0.007
38	1.359	1.352	0.007
39	1.345	1.352	0.007
40	1.369	1.400	0.031
41	0.990	0.946	0.045
42	0.856	1.083	0.227
43	1.352	1.297	0.055
44	1.397	1.404	0.007
45	1.331	1.328	0.003
46	1.376	1.383	0.007
47	1.373	1.376	0.003
48	1.355	1.362	0.007
49	1.321	1.352	0.031
50	1.321	1.318	0.003

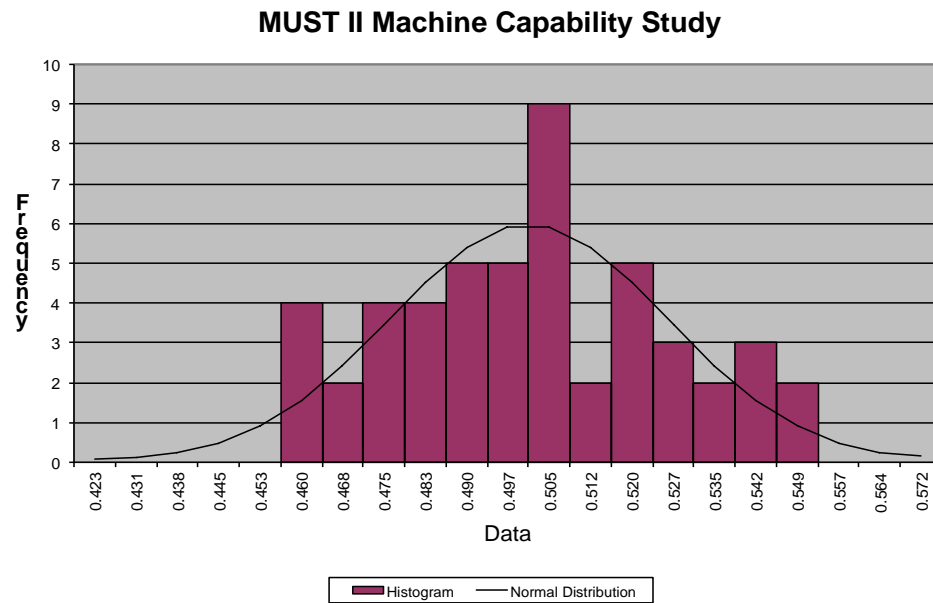
The instability of the graph lines was happening throughout the test and from Figure 4.4 there was evidence of this instability between F1 and F2. The range of the differences of the forces at 2 seconds and 5 seconds were analysed. Table 4.4 shows the F1 and F2 values and also the difference between each. The range value of the differences was 0.25mN. This result showed that the range between three seconds of testing (force at two seconds and



force at 5 seconds) was 0.25mN that caused the erratic spikes on the graph lines. The next investigation was to determine what was causing this instability. Given the fact that Ta and Tb showed good stable results and also the fact that the standard deviation for F1 and F2 was small it seemed at this stage that some external influence was affecting the readings.

#### 4.3.4 Machine Capability

The Machine Capability was assessed using the same fifty readings that were used to assess the X-BAR and R-Charts for Ta and Tb. Figure 4.6 is a graphical representation of a Capability Study for the fifty readings.



**Figure 4.7 Normal Distribution MUST II Wetting Balance Machine**

The results show a Normal Distribution of the results. Using an Upper Specification Limit (USL) of 0.6 and a Lower Specification Limit (LSL) of 0.3  $C_p$  and  $C_{pk}$  values were calculated. The USL and LSL limits of 0.6 and 0.3 were taken from the actual specification limits as stated in the IPC standards of  $\leq 0.6$  seconds, which is from 0 seconds to 0.6 seconds. A specification limit of between 0.3 and 0.6 was used in this case.

$$C_p = \frac{USL - LSL}{6\sigma}$$

.....Eq-4.5

$$C_p = \frac{0.6 - 0.3}{6 \times 0.025} = 2.02$$

A  $C_p$  value of 2.02 is an excellent value and meets the requirement of  $\geq 1.33$  [80]. For  $C_{pk}$  the value is taken as the smaller of either  $C_{pl}$  or  $C_{pu}$ .

$$C_{pl} = \frac{-LSL}{3}$$

.....Eq-4.6

$$C_{pl} = \frac{0.497 - 0.3}{3 \times 0.025} = 2.62$$

$$C_{pu} = \frac{USL -}{3}$$

....Eq-4.7

$$C_{pu} = \frac{0.6 - 0.497}{3 \times 0.025} = 1.37$$

With the lower value between  $C_{pu}$  and  $C_{pl}$  at 1.37, it can be determined that this is the  $C_{pk}$  of the MUST II machine. This value is an excellent indicator and achieves the machine capability requirements. [80] However the unstableness of the graph in Figure 4.4 was still a concern that required further investigation.

A  $C_p$  of 2.02 and a  $C_{pk}$  value of 1.37 prove the MUST II machine was capable and repeatable, but it was not the root cause for the erratic lines on the Wetting Balance graph in Figure 4.4. Another external factor or a combination of factors was causing this unstable behaviour and would require further investigation in order to determine the root cause.

#### 4.4 Improve Phase

During the Analysis Phase it was determined that there was a factor or a combination of factors affecting the readings. Even though the results for Ta and Tb achieved stable values in X-Bar and R-Charts, the graphical lines in Figure 4.4 displayed an instability which was further supported by the range between the F1 and F2 readings, 0.25mN.

The MUST II Wetting Balance machine is located in a laboratory where machines such as an X-Ray, Force tester and a mini SMT (Surface Mount Technology) line are constantly in operation during weekdays. There was no reference to any special location requirements for the Wetting Balance machine within any documentation from the supplier. However, when the results of this investigation were discussed directly with the machine supplier, they accepted that it was an important point that would be included in the next revision of the documentation.

In order to assess if the operation of these machines had any affect on the results, fifty measurements using the same procedure were repeated when all other machines within the laboratory were powered off. Ta, Tb, F1 and F2 were again used with copper leads to assess the machine repeatability and also the stability of the Wetting Balance graphs.

##### 4.4.1 Time to reach buoyancy line, Ta, No Vibrations

Using the readings from the repeated fifty measurements, new UCL and LCL limits were calculated and the results represented using X-Bar and R-Charts.

**X-Bar Control Chart Calculations:**

$$UCL = \bar{X} + (A_2 * \bar{R}) \dots \text{Eq-4.1}$$

$$UCL = 0.505 + (1.88 * 0.036)$$

$$UCL = 0.573$$

$$LCL = \bar{X} - (A_2 * \bar{R}) \dots \text{Eq-4.2}$$

$$LCL = 0.505 - (1.88 * 0.036)$$

$$LCL = 0.438$$

**R-Chart Calculations:**

$$UCL = D_4 * \bar{R} \dots \text{Eq-4.3}$$

$$UCL = 3.267 * 0.036$$

$$UCL = 0.118$$

$$LCL = D_3 * \bar{R} \dots \text{Eq-4.4}$$

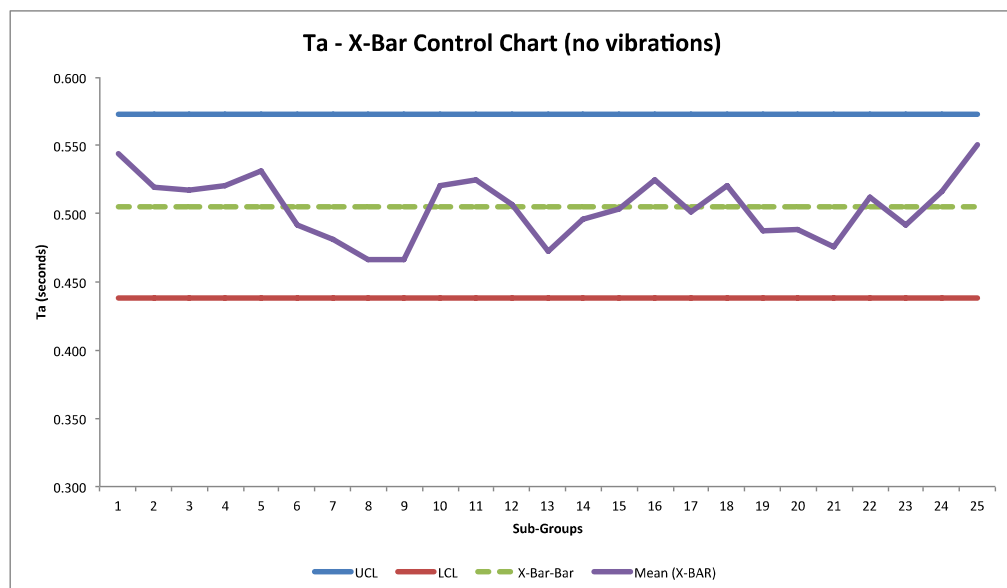
$$LCL = 0 * 0.036$$

$$LCL = 0$$

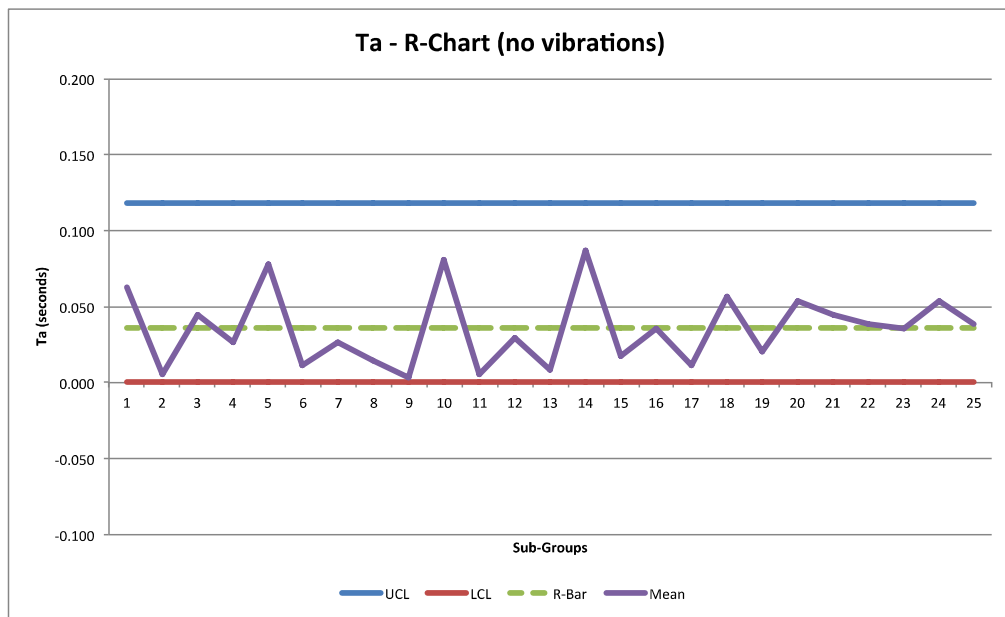
Table 4.5 is an overview of the 50 readings with the UCL and LCL limits for X-Bar and R-Charts from the calculations above.

**Table 4.5 Ta Results – X-Bar and R-Charts (no vibrations)**

No.	Ta Results from MUST II		Mean (X-BAR)	Max	Min	Range	X-BAR Control CHART				R-Control Chart			
							UCL	LCL	X-Bar-Bar	Mean (X-BAR)	UCL	LCL	R-Bar	Mean
1	0.513	0.576	0.544	0.576	0.513	0.063	0.573	0.438	0.505	0.544	0.118	0.000	0.036	0.063
2	0.516	0.522	0.519	0.522	0.516	0.006	0.573	0.438	0.505	0.519	0.118	0.000	0.036	0.006
3	0.495	0.540	0.518	0.540	0.495	0.045	0.573	0.438	0.505	0.518	0.118	0.000	0.036	0.045
4	0.534	0.507	0.521	0.534	0.507	0.027	0.573	0.438	0.505	0.521	0.118	0.000	0.036	0.027
5	0.492	0.570	0.531	0.570	0.492	0.078	0.573	0.438	0.505	0.531	0.118	0.000	0.036	0.078
6	0.486	0.498	0.492	0.498	0.486	0.012	0.573	0.438	0.505	0.492	0.118	0.000	0.036	0.012
7	0.495	0.468	0.481	0.495	0.468	0.027	0.573	0.438	0.505	0.481	0.118	0.000	0.036	0.027
8	0.459	0.474	0.466	0.474	0.459	0.015	0.573	0.438	0.505	0.466	0.118	0.000	0.036	0.015
9	0.465	0.468	0.466	0.468	0.465	0.003	0.573	0.438	0.505	0.466	0.118	0.000	0.036	0.003
10	0.480	0.561	0.521	0.561	0.480	0.081	0.573	0.438	0.505	0.521	0.118	0.000	0.036	0.081
11	0.528	0.522	0.525	0.528	0.522	0.006	0.573	0.438	0.505	0.525	0.118	0.000	0.036	0.006
12	0.492	0.522	0.507	0.522	0.492	0.030	0.573	0.438	0.505	0.507	0.118	0.000	0.036	0.030
13	0.477	0.468	0.472	0.477	0.468	0.009	0.573	0.438	0.505	0.472	0.118	0.000	0.036	0.009
14	0.540	0.453	0.497	0.540	0.453	0.087	0.573	0.438	0.505	0.497	0.118	0.000	0.036	0.087
15	0.513	0.495	0.504	0.513	0.495	0.018	0.573	0.438	0.505	0.504	0.118	0.000	0.036	0.018
16	0.543	0.507	0.525	0.543	0.507	0.036	0.573	0.438	0.505	0.525	0.118	0.000	0.036	0.036
17	0.507	0.495	0.501	0.507	0.495	0.012	0.573	0.438	0.505	0.501	0.118	0.000	0.036	0.012
18	0.492	0.549	0.521	0.549	0.492	0.057	0.573	0.438	0.505	0.521	0.118	0.000	0.036	0.057
19	0.498	0.477	0.487	0.498	0.477	0.021	0.573	0.438	0.505	0.487	0.118	0.000	0.036	0.021
20	0.516	0.462	0.489	0.516	0.462	0.054	0.573	0.438	0.505	0.489	0.118	0.000	0.036	0.054
21	0.498	0.453	0.476	0.498	0.453	0.045	0.573	0.438	0.505	0.476	0.118	0.000	0.036	0.045
22	0.531	0.492	0.512	0.531	0.492	0.039	0.573	0.438	0.505	0.512	0.118	0.000	0.036	0.039
23	0.510	0.474	0.492	0.510	0.474	0.036	0.573	0.438	0.505	0.492	0.118	0.000	0.036	0.036
24	0.543	0.489	0.516	0.543	0.489	0.054	0.573	0.438	0.505	0.516	0.118	0.000	0.036	0.054
25	0.570	0.531	0.551	0.570	0.531	0.039	0.573	0.438	0.505	0.551	0.118	0.000	0.036	0.039
Sum of Mean (X-BAR)			12.633	Sum of Range		0.900								
X-BAR-BAR			0.505	R-BAR		0.036								



**Figure 4.8 X-Bar Control Chart for Ta, No Vibrations**



**Figure 4.9 R-Bar Chart for Ta, No Vibrations**

Again both graphical representations in Figures 4.6 and 4.7 demonstrate results of a stable process.

#### 4.4.2 Time to reach Zero line, Tb, No Vibrations

The UCL and LCL limits were recalculated for Tb with the 50 readings taken when surrounding equipment was switch off.

##### X-Bar Control Chart Calculations:

$$UCL = \bar{X} + (A_2 * \bar{R}) \dots \text{Eq-4.1}$$

$$UCL = 0.531 + (1.88 * 0.038)$$

$$UCL = \underline{0.602}$$

$$LCL = \bar{X} - (A_2 * \bar{R}) \dots \text{Eq-4.2}$$

$$LCL = 0.531 - (1.88 * 0.038)$$

$$LCL = \underline{0.460}$$

##### R-Chart Calculations:

$$UCL = D_4 * \bar{R} \dots \text{Eq-4.3}$$

$$UCL = 3.267 * 0.038$$

$$UCL = \underline{0.124}$$

$$LCL = D_3 * \bar{R} \dots \text{Eq-4.4}$$

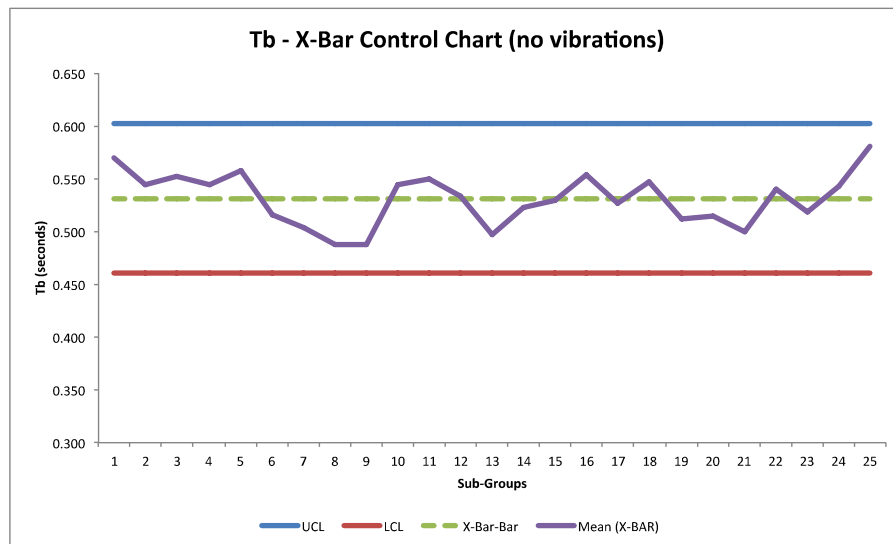
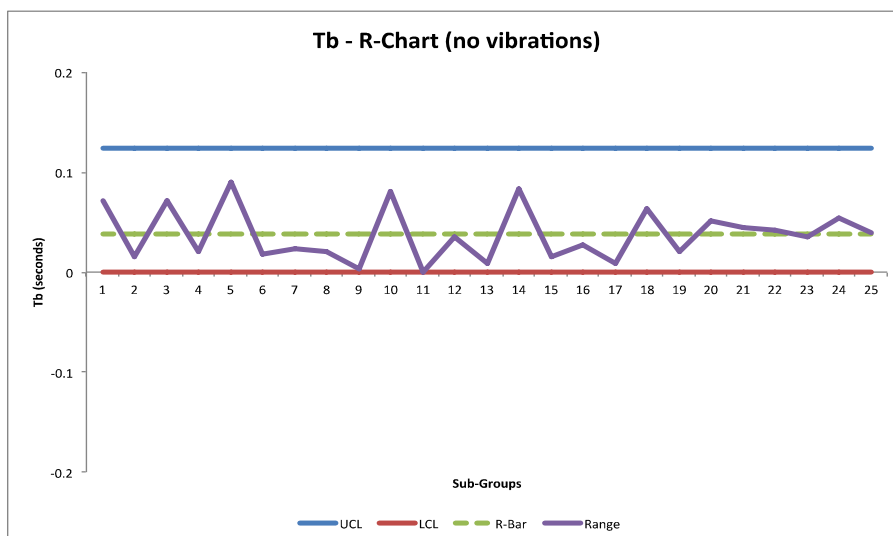
$$LCL = 0 * 0.038$$

$$LCL = \underline{0}$$

Table 4.6 is an overview of the 50 readings including the UCL and LCL limits for the X-Bar and R-Charts.

**Table 4.6 Tb Results – X-Bar and R-Charts (no vibrations)**

No.	Tb Results from MUST II		Mean (X-BAR)	Max	Min	Range	X-BAR Control CHART				R-Control Chart			
							UCL	LCL	X-Bar-Bar	Mean (X-BAR)	UCL	LCL	R-Bar	Range
1	0.534	0.606	0.570	0.606	0.534	0.072	0.602	0.46	0.531	0.570	0.124	0	0.038	0.072
2	0.537	0.552	0.544	0.552	0.537	0.015	0.602	0.46	0.531	0.544	0.124	0	0.038	0.015
3	0.516	0.588	0.552	0.588	0.516	0.072	0.602	0.46	0.531	0.552	0.124	0	0.038	0.072
4	0.555	0.534	0.544	0.555	0.534	0.021	0.602	0.46	0.531	0.544	0.124	0	0.038	0.021
5	0.513	0.603	0.558	0.603	0.513	0.090	0.602	0.46	0.531	0.558	0.124	0	0.038	0.090
6	0.507	0.525	0.516	0.525	0.507	0.018	0.602	0.46	0.531	0.516	0.124	0	0.038	0.018
7	0.516	0.492	0.504	0.516	0.492	0.024	0.602	0.46	0.531	0.504	0.124	0	0.038	0.024
8	0.477	0.498	0.487	0.498	0.477	0.021	0.602	0.46	0.531	0.487	0.124	0	0.038	0.021
9	0.486	0.489	0.487	0.489	0.486	0.003	0.602	0.46	0.531	0.487	0.124	0	0.038	0.003
10	0.504	0.585	0.544	0.585	0.504	0.081	0.602	0.46	0.531	0.544	0.124	0	0.038	0.081
11	0.549	0.549	0.549	0.549	0.549	0.000	0.602	0.46	0.531	0.549	0.124	0	0.038	0.000
12	0.516	0.552	0.534	0.552	0.516	0.036	0.602	0.46	0.531	0.534	0.124	0	0.038	0.036
13	0.501	0.492	0.497	0.501	0.492	0.009	0.602	0.46	0.531	0.497	0.124	0	0.038	0.009
14	0.564	0.480	0.522	0.564	0.480	0.084	0.602	0.46	0.531	0.522	0.124	0	0.038	0.084
15	0.537	0.522	0.530	0.537	0.522	0.015	0.602	0.46	0.531	0.530	0.124	0	0.038	0.015
16	0.567	0.540	0.554	0.567	0.540	0.027	0.602	0.46	0.531	0.554	0.124	0	0.038	0.027
17	0.531	0.522	0.527	0.531	0.522	0.009	0.602	0.46	0.531	0.527	0.124	0	0.038	0.009
18	0.516	0.579	0.548	0.579	0.516	0.063	0.602	0.46	0.531	0.548	0.124	0	0.038	0.063
19	0.522	0.501	0.512	0.522	0.501	0.021	0.602	0.46	0.531	0.512	0.124	0	0.038	0.021
20	0.540	0.489	0.515	0.540	0.489	0.051	0.602	0.46	0.531	0.515	0.124	0	0.038	0.051
21	0.522	0.477	0.500	0.522	0.477	0.045	0.602	0.46	0.531	0.500	0.124	0	0.038	0.045
22	0.561	0.519	0.540	0.561	0.519	0.042	0.602	0.46	0.531	0.540	0.124	0	0.038	0.042
23	0.537	0.501	0.519	0.537	0.501	0.036	0.602	0.46	0.531	0.519	0.124	0	0.038	0.036
24	0.570	0.516	0.543	0.570	0.516	0.054	0.602	0.46	0.531	0.543	0.124	0	0.038	0.054
25	0.600	0.561	0.581	0.600	0.561	0.039	0.602	0.46	0.531	0.581	0.124	0	0.038	0.039
Sum of Mean (X-BAR)			13.275	Sum of Range			0.948							
X-BAR-BAR			0.531	R-BAR			0.038							

**Figure 4.10 X-Bar Control Chart for Tb, No Vibrations****Figure 4.11 R-Bar Chart for Ta, No Vibrations**

Comparing Figure 4.4 (machines powered on) to the graph in Figure 4.10 (machines powered off) the effect of the other equipment within the vicinity of the Wetting Balance machine caused vibrations that resulted in the ‘unstable’ lines in Figure 4.4. This unstableness would easily influence the force and time measurements and was certain to cause measurement errors. In order to support this theory, the range between for F1 and F2 would need to be assessed to determine if there was any significant improvement.

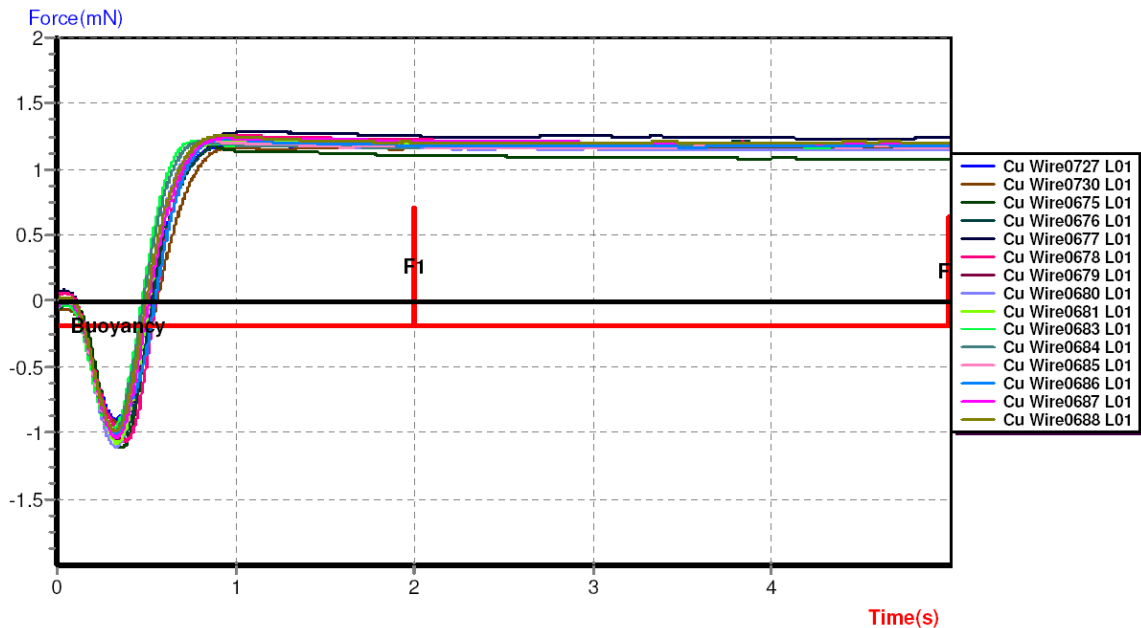


Figure 4.12 Fifteen readings from the fifty measurements - all machine powered off

#### 4.4.3 F1 and F2

Table 4.7 shows the F1, F2 and the difference between both for all fifty measurements.

Table 4.7 F1 and F2 Results

No.	F1	F2	Difference F1 & F2
1	1.349	1.359	0.010
2	1.345	1.349	0.003
3	1.287	1.259	0.028
4	1.404	1.386	0.017
5	1.438	1.424	0.014
6	1.410	1.383	0.028
7	1.373	1.369	0.003
8	1.345	1.331	0.014
9	1.380	1.359	0.021
10	1.362	1.362	0.000
11	1.352	1.376	0.024
12	1.359	1.349	0.010
13	1.366	1.362	0.003
14	1.400	1.390	0.010
15	1.393	1.390	0.003
16	1.345	1.318	0.028
17	1.373	1.352	0.021
18	1.393	1.390	0.003
19	1.435	1.414	0.021
20	1.355	1.349	0.007
21	1.390	1.383	0.007
22	1.342	1.324	0.017
23	1.438	1.441	0.003
24	1.342	1.324	0.017
25	1.355	1.362	0.007
26	1.400	1.407	0.007
27	1.318	1.300	0.017
28	1.369	1.362	0.007
29	1.373	1.342	0.031
30	1.393	1.383	0.010
31	1.407	1.407	0.000
32	1.314	1.304	0.010
33	1.373	1.383	0.010
34	1.369	1.369	0.000
35	1.400	1.404	0.003
36	1.380	1.393	0.014
37	1.386	1.393	0.007
38	1.328	1.311	0.017
39	1.359	1.362	0.003
40	1.380	1.404	0.024
41	1.404	1.410	0.007
42	1.331	1.321	0.010
43	1.393	1.383	0.010
44	1.345	1.345	0.000
45	1.359	1.321	0.038
46	1.393	1.400	0.007
47	1.366	1.362	0.003
48	1.338	1.335	0.003
49	1.417	1.421	0.003
50	1.369	1.380	0.010

The range was 0.037mN. This value reduced from 0.25mN when the external influences from the machines within the lab caused the MUST II to give erratic readings.

## 4.5 Control Phase

The experimentation into the repeatability of the MUST II Wetting Balance machine established that vibrations from other sources such as the X-Ray and SMT equipment within the vicinity had very significant effects on its performance in terms of accuracy and repeatability. These external influences needed to be eliminated for the duration of the testing while using the Wetting Balance machine. As mentioned earlier in the chapter, the measurements for a Wetting Balance machine are miniature, milli-newtons (mN), and any error in the machines readings could have a major impact on the measurements, thus giving false readings and impacting the results.

In order to ensure stability and control of the results when carrying out solderability testing with a Wetting Balance machine, the following precautions must be adhered to is:

- Ensure all other equipment within the location of the Wetting Balance machine is powered off to avoid unnecessary influences such as vibrations while testing.
- If this is not possible, locate the Wetting Balance machine in a room that is not located near any equipment that may affect the results.

The supplier of the MUST II recommends that the machine is located in an area where there is no other equipment that could potentially cause vibrations.

## 4.6 Conclusions

The main focus of the analysis in the chapter was to determine if the Wetting Balance machine was capable of providing repeatable and accurate results. It is imperative that a system has a datum to be measured against when analysing any process. In this case the  $T_b$ , time to reach the zero line in <1 second, and  $T_a$ , time to buoyancy in <0.6 seconds, were used and the specifications quoted were got from the international standards.

For  $T_b$  and  $T_a$ , X-Bar and R-Charts were developed from 50 readings on the MUST II Wetting Balance machine. The graphs provided excellent results but it was noted that there was some influence causing unstableness in the graphs. A  $C_p$  value 2.02 and a  $C_{pk}$  value 1.37 demonstrate the MUST II machine was reliable, capable and repeatable but was not a root cause of the erratic lines on the Wetting Balance graph in Figure 4.4. Further analysis was required to understand and eliminate the unstableness in the graphs. The forces at two seconds (F1) and at five seconds (F2) were then analysed and it was concluded that the range of 0.25mN was very high.

The location of the Wetting Balance machine proved to be the critical and vibrations from any equipment located near should be maintained to a minimum in order to eliminate the risk of impacting the results. The elimination of vibrations is of paramount importance when developing a stabilised system for testing the solderability using a Wetting Balance machine due to the small margin for error. From the lessons learned in this chapter a more detailed experimentation can be conducted with a high level of confidence that the machine readings are accurate and consistent.

The stableness of the Wetting Balance graphs significantly improved and for Tb and Tb, are still excellent results. X-Bar and R-Chart were recreated once all vibrations within the vicinity of the Wetting Balance machine were powered off. The results were stable and reliable providing a high level of confidence for the machine operation. The range value for F1 and F2 reduced significantly to 0.037mN during the three seconds test time. This Chapter has now determined that the equipment to be used, MUST II Wetting Balance machine, is a reliable and robust process.

The results were conclusive and highlighted the key areas in terms of assessing machine repeatability and accuracy, which must be considered prior to conducting any experiments on the Wetting Balance machine.



## Chapter 5 Wetting Balance Test Evaluation – Screening DoE

### 5.0 Introduction

From the investigations and resulting conclusions in Chapter 3, it was determined that the ‘Dip & Look’ solderability test serves no purpose in evaluating a components soldering ability. Another globally recognised test used to access a component’s solderability is the ‘Wetting Balance Test’. The Wetting Balance test provides much more useful information than the Dip & Look test. It investigates the speed and extent of wetting during the entire dipping process whereas the Dip & Look test only gives the result of wetting, ‘Pass’ or ‘Fail’, at the end of the test.

However, as no generally accepted method for evaluating the wetting force curves exist, it was decided to investigate this test in more detail using 0.9mm diameter copper wires that were pre-coated with the alloy used in the solder bath. The reason for using copper wires was to reduce as much as possible any variations between component lead solderability. Feedback from the Wetting Balance machine manufacturer stated the main factors that influence the soldering characteristics for the Wetting Balance test are:

- Solder temperature (°C)
- Immersion depth (mm)
- Immersion speed (mm/sec)
- Dwell time (seconds)
- Removal speed (mm/sec)

Similar to the Dip & Look test investigation, there are no defined set of parameter settings that will provide an optimum result for the following responses:

- 1) Ta – Time to buoyancy (seconds)
- 2) Tb – Time to cross zero line (seconds)
- 3) Fmax – Maximum Force (mN)
- 4) TFmax – Time to reach maximum force (seconds)
- 5) F1 – Force after 2 seconds (mN)
- 6) F2 – Force after 5 seconds (mN)

Time to reach two-thirds of the maximum force is another response associated with the Wetting Balance test but for this project was not included in any analysis. Instead the time to reach the maximum force was assessed. The parameter settings stated in the various international standards have conflicting settings for the different parameters in question in a SnPb and a SAC process. The SN100C alloy is not referenced within the standards so the same recommended settings for the SAC alloy were used because both are lead-free alloys.

The only difference was the solder bath temperature. SN100C has a peak temperature of 260<sup>0</sup>C and SAC305 has a peak temperature of 255<sup>0</sup>C. One concern was the fact that the range of settings for each parameter was so large that the results of the Wetting Balance test could vary considerably depending on the array of settings used and this needed to be investigated. As the Wetting Balance test results are in milli-newtons (mN) for force and seconds for time, the range of settings should be minimal to avoid any significant variation. Table 5.1 is an overview of the range of settings from each standard.

**Table 5.1 Overview of International Standards**

Standard	Test	Name	Immersion Depth	Angle	Immersion Speed	Dwell Time	Solder Temp	Solder Composition	Preconditioning
J-STD-002C	E	Tin/lead Solder - Wetting Balance Solder Pot Test (lead components)	0.1mm	20-45 for SMT / 90 for TH (same for wire)	1-5mm/sec	5+/- 0.5sec	245+/- 5Deg	Sn60Pb40 or Sn63Pb37	Not required
J-STD-002C	E1	Lead-free Solder - Wetting Balance Solder Pot Test (lead components)	0.1mm	20-45 for SMT / 90 for TH (same for wire)	1-5mm/sec	5+/- 0.5sec	255+/- 5Deg	SAC305	Not required
J-STD-002C	G	Tin/lead Solder - Wetting Balance Solder Pot Test (lead components)	Fully Immersed	20-45 for SMT / 90 for TH (same for wire)	1-5mm/sec	5+/- 0.5sec	245+/- 5Deg	Sn60Pb40 or Sn63Pb37	Not required
J-STD-002C	G1	Tin/lead Solder - Wetting Balance Solder Pot Test (lead components)	Fully Immersed	20-45 for SMT / 90 for TH (same for wire)	1-5mm/sec	5+/- 0.5sec	255+/- 5Deg	SAC305	Not required
JESD22-B102D	B102D	Solderability - Lead and Lead-free (Solder Bath)	Fully Immersed	20-45 for SMT / 90 for TH (same for wire)	25.4+/- 6.4mm/sec	5+/- 0.5sec	245+/- 5degC or 255+/- 5degC	Sn60Pb40 or Sn63Pb37 / SAC305	150deg high temp bake
IEC68-2-69	6.2	Solderability testing of electronic components for surface mount technology by the wetting balance method - Solder bath method	0.1mm	20-45 for SMT / Vertical	1-5mm/sec	5sec	235+/- 3deg	Sn60Pb40	If required by component specification
IEC68-2-69	6.3	Solderability testing of electronic components for surface mount technology by the wetting balance method - Solder globule method	0.25	20-45 for SMT / Vertical	1-5mm/sec	5sec	235+/- 3deg	Sn60Pb40	If required by component specification
IEC68-2-54	N/A	Solderability testing of electronic components for surface mount technology by the wetting balance method - Solder bath method	2-5mm	20-45 for SMT / Vertical	5mm/sec +/- 1mm/sec to 20mm/sec +/- 1mm/sec	0-10sec	235+/- 3deg or 245+/- 3deg	Sn60Pb40 or Sn63Pb37 / SAC305	As per IEC60068-2-20

As stated earlier, the two most common solderability tests used by component suppliers are the ‘Dip & Look’ and the ‘Wetting Balance test’. Depending on the component supplier, different settings can be used for the different parameters, solder temperature, immersion speed, immersion depth, and dwell time, which may lead to a variation in the results and also no repeatability. Therefore it is extremely important that the Wetting Balance test be investigated and proven to get the optimum settings for the different parameters. Both the component supplier and a consumer can then use these optimum settings to assess the components soldering characteristics.

## 5.1 Experimental Aims

The experimental aims of this section of the projects were:

1. To determine and eliminate the non-critical variables which are currently used when assessing solderability by means of the Wetting Balance machine. The current variables are:
  - Solder temperature (°C)
  - Immersion depth (mm)
  - Immersion speed (mm/sec)
  - Dwell time (seconds)
  - Removal speed (mm/sec)
2. To determine the effect each of the responses,  $T_b$ ,  $T_a$ ,  $F_{max}$ ,  $TF_{max}$ ,  $F_1$ , and  $F_2$  have on each of the above-mentioned variables in a SN100C process.

Eliminating the non-critical variables in this chapter will provide the framework for a detailed DoE in Chapter 6 that will evaluate the Wetting Balance machine and test. Ascertaining the effect, if any, each of the responses have on the aforementioned variables will provide the basis for which a more detailed analysis can be conducted in subsequent chapters.

## 5.2 Planning Phase

In order to achieve the aforementioned objectives, each of the standards listed in Table 5.1 were reviewed to determine the variation of each parameter, solder temperature, immersion speed, immersion depth, dwell time and removal speed in a SN100C process using a solder bath. As mentioned earlier, with the introduction of the WEEE, RoHS, and ELV Directives all products are now designed with lead-free capability. SN100C was the principal alloy used by the company for whom this project was done and this was also used for all Wetting Balance testing in this project.

The solder globule method was not analysed because of the restriction in the immersion depth setting. The solder globule method is mostly used for SMT components. Each of the four standards do not state that preconditioning of the test samples (copper wires) is a requirement and for this reason preconditioning is not included in any of the Design of Experiment's (DoE's).

1. IEC 60068-2-54 – Solderability testing of electronic components by the Wetting Balance method (Solder Bath) in a Sn60Pb40 or Sn63Pb37 / SAC305 process.
2. IEC 60068-2-69 Environment Testing – Part 2: Tests – Test Te: Solderability testing of electronic components for surface mount technology by the Wetting

Balance method (Solder Bath Method & Solder Globule Method) in a Sn60Pb40 process.

3. IPC J-STD-002C – Solderability Test for Component Leads, Terminations, Lugs, Terminals and Wires (Solder Bath Method & Solder Globule Method) in a Sn60Pb40 or Sn63Pb37 / SAC305 process.
4. JESD22-B102D – Solderability - Lead and Lead-Free (Solder Bath) in a Sn60Pb40 or Sn63Pb37 / SAC305 process.

This variation, see Table 5.1, was analysed for each of the alloys with a screening Design of Experiments followed by a more in-depth DoE. For each of the screening DoE's, two levels (min/max) and three replicates were used giving a total of 24 runs. Three repetitions were used for each run. An explanation of the DOE and the outcomes are discussed later in the chapter. Appendix 5 shows the full array of runs. The following procedure was used to test the components using the Wetting Balance machine.

1. Log on using the desktop shortcut to 'MUST II'.
2. Using the tool menu input the various parameters for the factors using the arrays in Appendix 4 illustrates the arrays for the run combinations.
3. Attach the copper wire to the clip using gloves. The use of gloves will prevent contamination on the copper surface.
4. Press 'Start Test' and follow the on screen instructions that are prompted by the MUST II.
5. When the testing is complete store the results in the default location on the hard-drive.

A more comprehensive procedure for the Wetting Balance test using the MUST II machine is in Appendix 5. For the DoE, copper wires of 20mm lengths were used. These were cut using a specially manufactured tool for ensuring the same repeated length and angle of cut. This would eliminate the possibility of further influences on the results such as varying lengths of copper wire and also the angle of cut when cutting the individual lengths from the reel.

### **5.2.1 Screening DoE – Solder Bath**

The parameter settings for DoE were obtained from a combination of international standards J-STD-002C test E1, JESD22-B102D, IEC668-2-69 and IEC68-2-54. Table 5.2 lists the minimum and maximum settings using a solder bath with SN100C solder.

**Table 5.2 Parameter settings from International Standards – Solder Bath**

Variable	Minimum	Maximum
Solder Temperature (°C)	240	260
Immersion Speed (mm/sec)	1	25
Dwell Time (sec)	5	10
Immersion Depth (mm)	3	5
Removal Speed (mm/sec)	1	25

### 5.3 Design of Experiments

The DoE was planned to include what was deemed (by various component suppliers) to be the necessary variables. A resolution III experiment was set-up and the objective was to screen the important variables and responses for further experimentation. Five variables were selected and were experimented at two levels ‘Low’ and ‘High’. These variables are listed in Table 5.2.

All other variables were held constant, i.e. solder type, Wetting Balance machine, Flux and other machine parameters. The number of responses analysed was six;

1. Tb – Time to cross x-axis (seconds)
2. Ta – Time to Buoyancy (seconds)
3. Fmax – Maximum Force (mN)
4. TFmax – Time to reach maximum force (seconds)
5. F1 – Force after 2 seconds (mN)
6. F2 – Force after 5 seconds (mN)

#### 5.3.1 Factors and Run Combinations

Table 5.2 shows the settings used for each run in the Design of Experiments. A MUST II Wetting Balance machine was used for completing all testing and the analysis of the results was done using Minitab software.

At the beginning of every run, the machine settings were made with reference to the arrays in Appendix 5. Once steady state conditions were achieved and settings verified, the run was initiated. Each run consisted of one copper wire. No preconditioning of the copper wires was carried out prior to the testing.

When the test was complete, the Wetting Balance machine automatically recorded the readings for Tb, Ta, Fmax, F1 and F2 and graphed the result for each of the run combinations, 1 to 24 for each of the three DoE's.

## 5.4 Analysis of Results

Appendix 6 shows the resulting Wetting Balance graphs for each of the run combinations in Appendix 5. Figure 5.1 is an example of the graph automatically presented by the Wetting Balance machine after the settings from these run combinations was used. As described in Chapter 2 this is a typical Wetting Balance curve throughout industry.

The average for each of the three results for Ta, Tb, F1, F2, Fmax and TFmax was calculated and this value was inputted to Minitab for analysis. For example if Ta is considered, the values recorded by the MUST II were 0.505, 0.480 and 0.445. The average for these is 0.477seconds. This was repeated for all the responses.

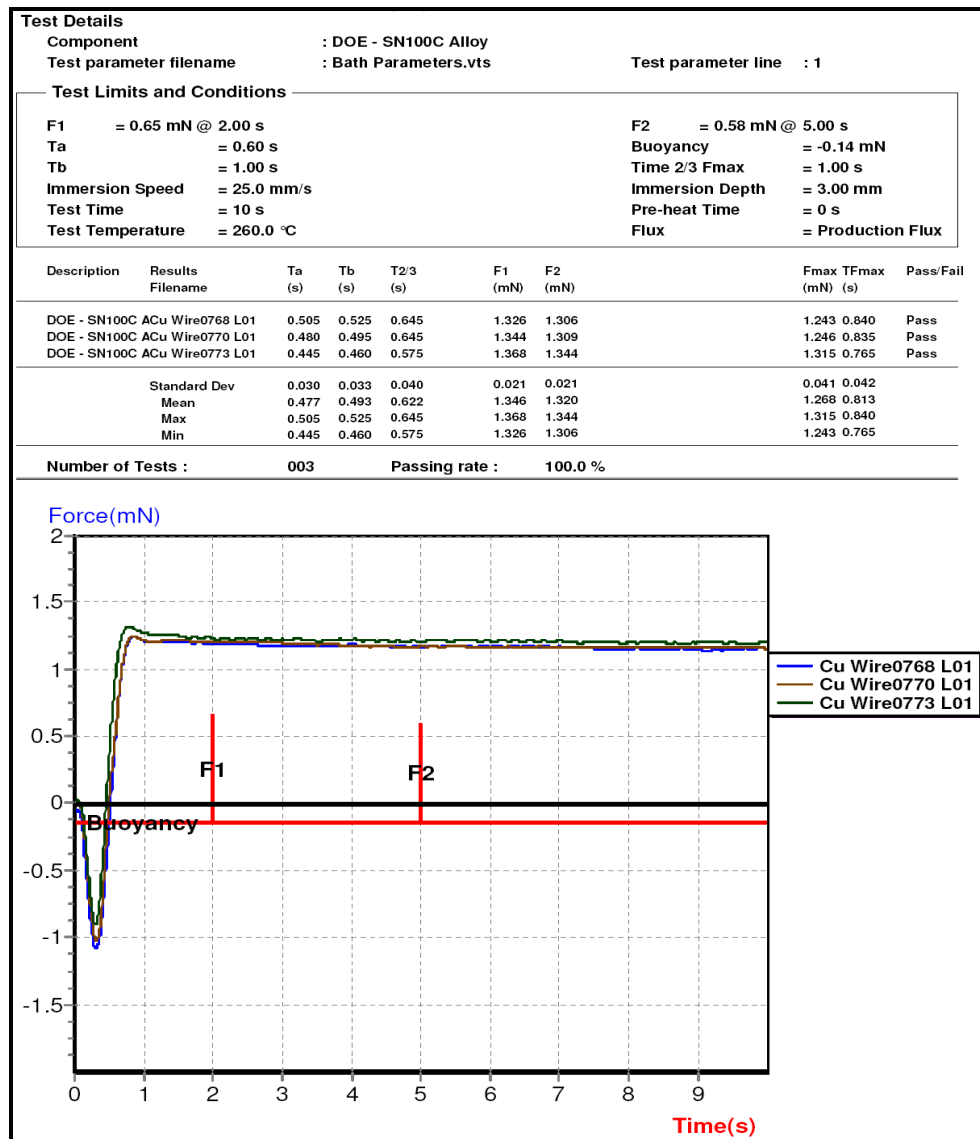


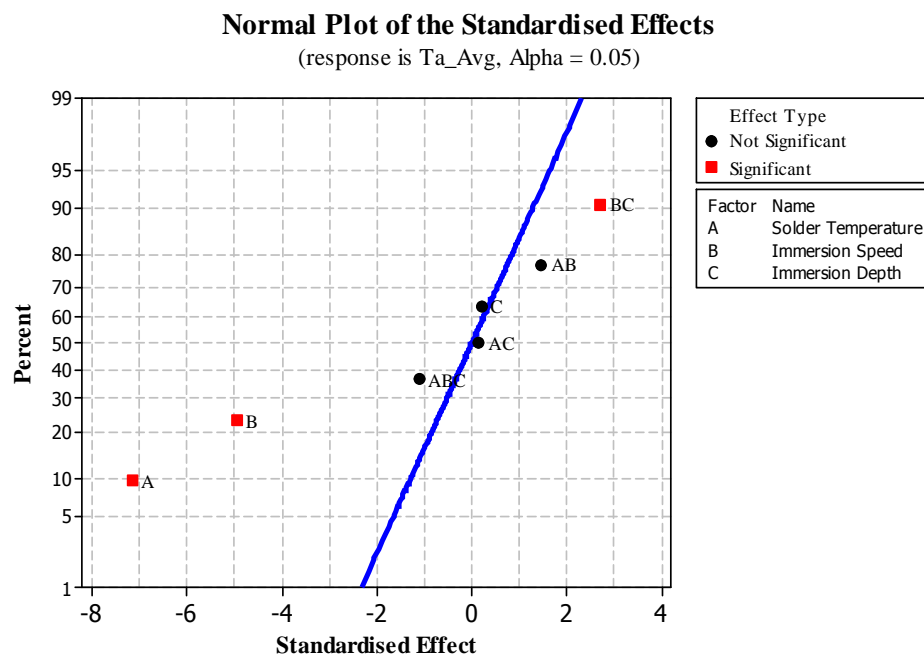
Figure 5.1 Wetting Balance Graph for Run 1

### 5.4.1 Time to Buoyancy (Ta) Results

Using a Normal Plot of the Standardised Effects to compare the relative magnitude and the statistical significance of both main and interaction effects, Minitab calculated solder

temperature (A), immersion speed (B) and an interaction between immersion speed and immersion depth (BC) as the factors that had the most significant effect on the time to buoyancy, Ta. Minitab draws a line to indicate where the points would be expected to fall if all effects were zero, Figure 5.2. Points that do not fall near the line usually signal significant effects. Such effects are larger and generally further from the fitted line than unimportant effects. By default, Minitab uses an alpha-level of 0.05 and labels any effect that is significant.

For the main DoE in Chapter 6 all three factors will be considered in order to get a more detailed analysis of each affect and also the relationship between immersion speed and immersion depth.

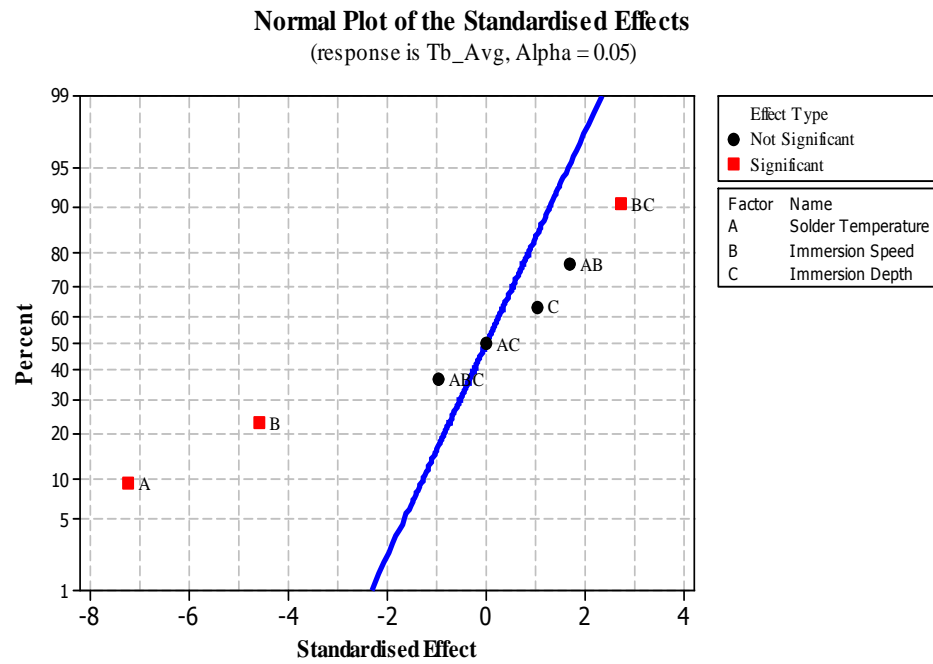


**Figure 5.2 Normal Plot of the Standardised Effects for Ta**

#### 5.4.2 Time to cross x-axis (Tb) Results

Minitab calculated the factors that had an effect of the time to cross the zero line using the same format as previously used for Ta, Normal Plot of the Standardised Effects. Again similar to the Ta response, Tb has the same factors and interaction of factors that show significant effects that are evident in Figure 5.3. These are solder temperature, immersion speed, and an interaction between immersion speed and immersion depth. They are located furthest away from the line and Minitab highlighted them in red as being significant.

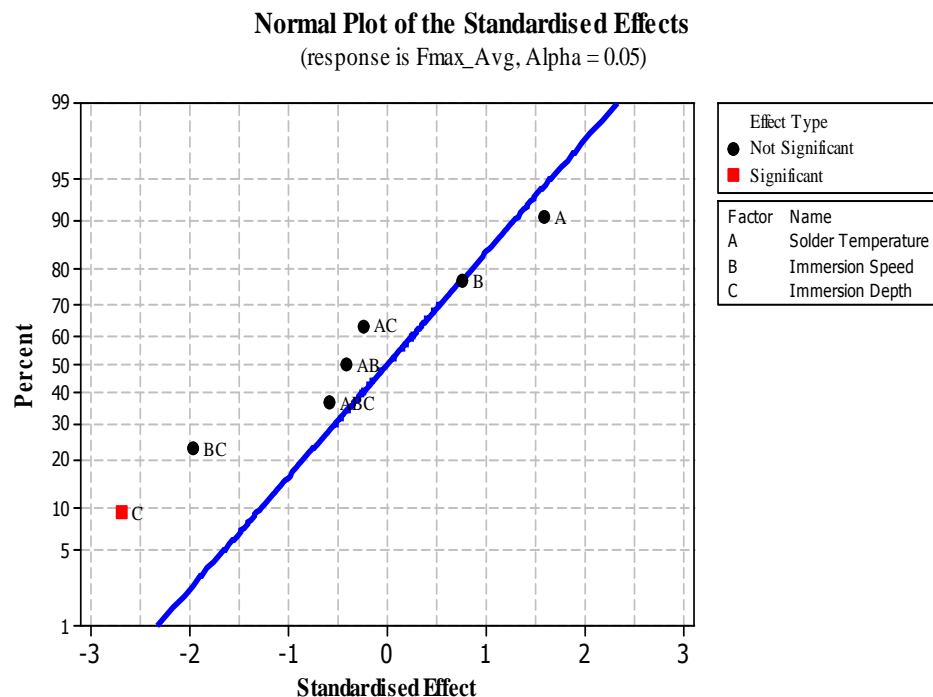
The similarity between the significant effects for Ta and Tb was expected because both responses are very comparable in terms of the J-Standard specification. Ta must be reached on or before 0.6seconds (buoyancy) and Tb on or before 1 second (zero line) on the Wetting Balance graph.



**Figure 5.3 Normal Plot of the Standardised Effects for Tb**

### 5.4.3 Maximum Force (Fmax) Results

Minitab calculated the factors that had an effect of the Fmax, the maximum force reached during the Wetting Balance test, as been only the immersion depth. However, Figure 5.4 shows that the interactions between BC, immersion speed (B) and immersion depth (C), are also located far from the line so it was decided to include these as part of the detailed DoE in the next chapter for further analysis.



**Figure 5.4 Normal Plot of the Standardised Effects for Fmax**



Referring to Appendix C in J-STD-002C a theoretical value for Fmax is calculated using the formula:

$$F_{\max} = [0.5P - 0.07V] \dots\dots\dots 5.1 \quad [7]$$

Where;

0.5P is the maximum force

0.5 is the surface tension ( $\gamma$ ) of SN100C solder

P is the circumference of the wire

0.07V is the buoyancy force

0.07 is the density ( $\rho$ ) of the SN100C solder

V is the immersed volume

Immersion depths of 3mm and 5mm used

$$\begin{aligned} P &= 2 \pi r \\ \Rightarrow P &= 2 \times \pi \times 0.45 \\ \Rightarrow P &= 2.8274 \text{ mm} \\ \Rightarrow P &= 2.83 \text{ mm} \end{aligned}$$

$$\begin{aligned} 0.5P &= 0.5 \times 2.83 \\ \Rightarrow 0.5P &= 1.415 \approx 1.42 \text{ mN} \end{aligned}$$

$$\begin{aligned} V &= \left( \frac{d^2}{4} \right) \times 3 \\ \Rightarrow V &= \left( \frac{(0.9)^2}{4} \right) \times 3 \\ \Rightarrow V &= (0.64 \times 3) \\ \Rightarrow V &= 1.91 \text{ mm}^3 \end{aligned}$$

$$\begin{aligned} \therefore 0.07V &= 0.07 \times 1.91 \\ \Rightarrow 0.07V &= 0.1337 \approx 0.13 \end{aligned}$$

$$\begin{aligned} \therefore F &= 1.42 - 0.13 \\ \Rightarrow F_{\max} &= 1.29 \text{ mN} \end{aligned}$$

$$\begin{aligned} V &= \left( \frac{d^2}{4} \right) \times 5 \\ \Rightarrow V &= \left( \frac{(0.9)^2}{4} \right) \times 5 \\ \Rightarrow V &= (0.64 \times 5) \\ \Rightarrow V &= 3.20 \text{ mm}^3 \end{aligned}$$

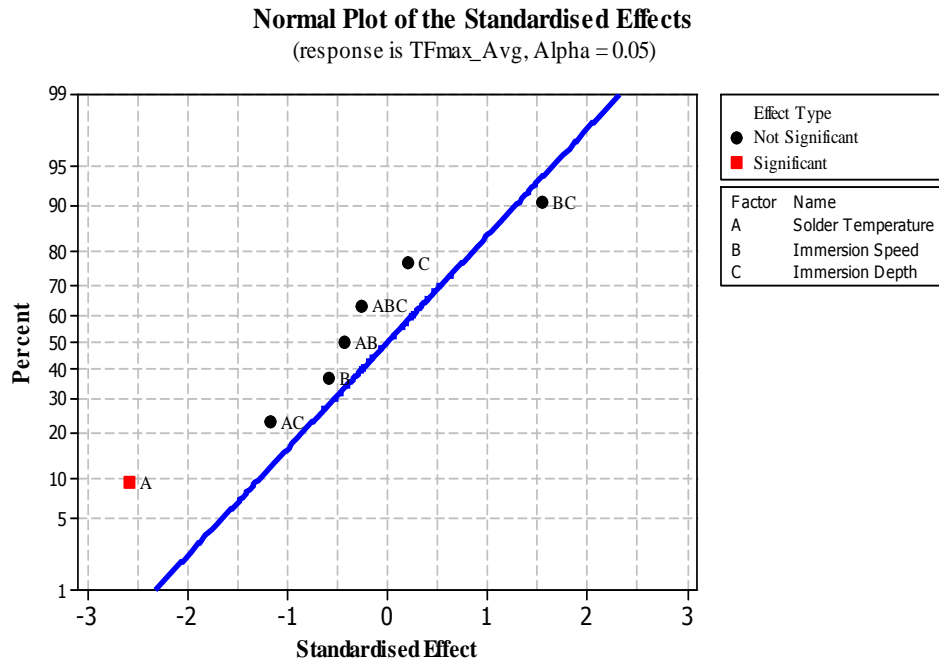
$$\begin{aligned} \therefore 0.07V &= 0.07 \times 3.20 \\ \Rightarrow 0.07V &= 0.224 \approx 0.22 \end{aligned}$$

$$\begin{aligned} \therefore F &= 1.42 - 0.22 \\ \Rightarrow F_{\max} &= 1.20 \text{ mN} \end{aligned}$$

The Fmax theoretical for a 0.9mm diameter copper wire immersion 3mm and 5mm is 1.29mN and 1.20mN respectively.

#### 5.4.4 Time to reach Maximum Force (TFmax) Results

Minitab again calculated the factors that had significant effects on the time to reach the maximum force, TFmax. Only the solder temperature had an effect on the TFmax response. The effect of all other factors was insignificant and these would not be included in the detailed analysis.



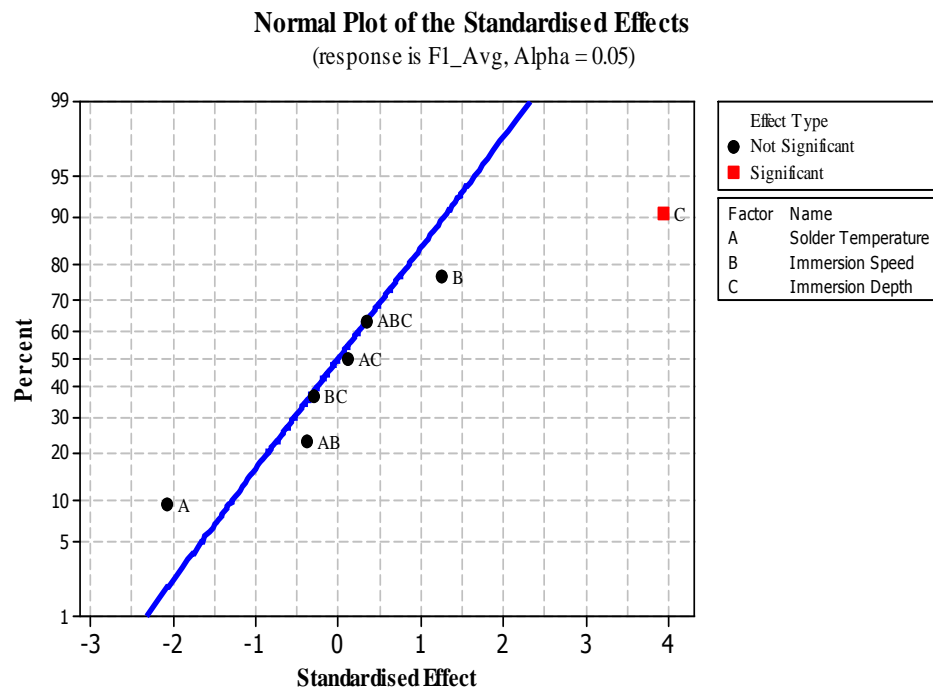
**Figure 5.5 Normal Plot of the Standardised Effects for TFmax**

#### 5.4.5 Force at 2 seconds (F1) Results

From Figure 5.6, the immersion depth was the only factor that had a significant effect on the force reached after two seconds of the Wetting Balance test. However, as the F2 significant effect also includes solder temperature and the graphical representation for both F1 and F2 are almost identical, solder temperature will be deemed significant and included for more analysis. The minimum requirement for F1 is a force of 0.65mN for an immersion depth of 3mm and 0.60N for an immersion depth of 5mm. The J-Standard-002C states that F1 (force after 2 seconds of testing) should be no less than 50% of the maximum force reach during the test. These are calculated as follows:

$$\begin{aligned}
 F1 &= F_{\max} \times 50\% \\
 \Rightarrow F1 &= 1.29 \times 50\% \\
 \Rightarrow F1 &= 0.65mN
 \end{aligned}$$

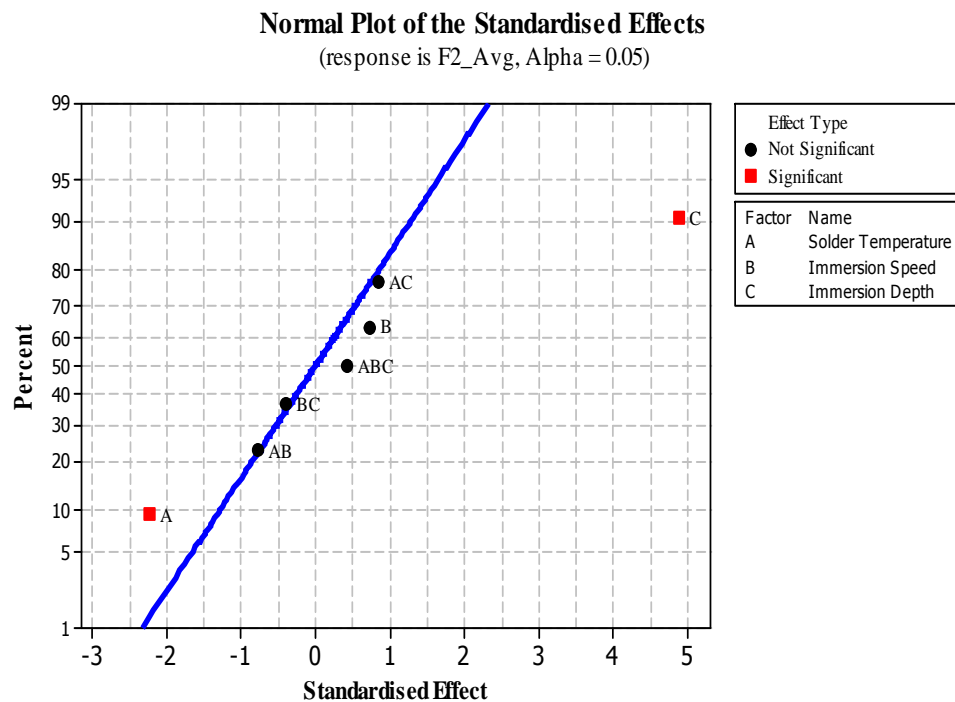
$$\begin{aligned}
 F1 &= F_{\max} \times 50\% \\
 \Rightarrow F1 &= 1.20 \times 50\% \\
 \Rightarrow F1 &= 0.60mN
 \end{aligned}$$



**Figure 5.6 Normal Plot of the Standardised Effects for F1**

#### 5.4.6 Force at 5 seconds (F2) Results

From Figure 5.7, the factors solder temperature and immersion depths were the only two that had a significant effect on the F2 readings. Both F1 and F2 are force reading at 2 and 5 seconds during the Wetting Balance test and in order to have positive wetting results, it is preferred to have F1 and F2 almost identical.



**Figure 5.7 Normal Plot of the Standardised Effects for F2**

The minimum requirement for F2 is a force of 0.58mN and 0.54mN for 3mm and 5mm immersion depths respectively. The J-Standard-002C states that F2 (force after 5 seconds of testing, dewetting) should be no less than 90% of the F1. This is calculated as follows:

$$F2 = F1 \times 90\%$$

$$\Rightarrow F1 = 0.65 \times 90\%$$

$$\Rightarrow F1 = 0.58mN$$

$$F2 = F1 \times 90\%$$

$$\Rightarrow F1 = 0.60 \times 90\%$$

$$\Rightarrow F1 = 0.54mN$$

## 5.5 Conclusions from Design of Experiment

The Screening DoE provided an analysis for each parameter and the affects on the six responses; Ta, Tb, Fmax, TFmax, F1 and F2. Many significant effects were evident but in order to get a more detailed in-depth analysis, a further Design of Experiments will be required. Each parameter will have three levels, low, medium and high and it is hoped that the medium level for each parameter will provide more information to help fully understand the effect of using different parameter settings will have on the responses.

From the analysis conducted in this chapter a number of significant conclusions can be made. It should be noted that all 0.9mm copper wire specimens soldered during the Wetting Balance test. However, the difference between each was established by the time to solder, Ta and Tb, and the amount of solder which wetted to the copper wires, Fmax, F1 and F2. So far the analysis has shown:

- For Ta and Tb – solder temperature, immersion speed and an interaction between immersion speed and immersion depth have a significant effect.
- For Fmax – immersion depth is the only significant factor highlighted. However, the interaction between immersion speed and immersion depth will also be considered because of its location from the best fit line on the Normal Plot of the Standardised Effects.
- For TFmax – Solder temperature is the only factor that presents an effect of the time to reach the maximum force.
- For F1 and F2 – Solder temperature and immersion depth both show significant effects on the forces at 2 and 5 seconds.

In order to get an in-depth understanding of the effect solder temperature, immersion speed and immersion depth have on each of the responses, Ta, Tb, Fmax, TFmax, F1 and F2 a subsequent Design of Experiments will be carried out with a greater number of levels and run combinations. Even though solder temperature, immersion speed and immersion depths do not have significant effects on some of the responses, all three will be included

in the more detailed DoE in Chapter 6. The ANOVA tables will determine if factors are to be included in the analysis for each of the responses.

It can also be concluded at this stage that the dwell time and removal speed can be eliminated from further consideration because for both of these factors the test is complete and the results recorded so therefore any variation of both factors will not affect the results. Also when conducting the experiment it was noted that the speed setting of 25mm/sec seem to be too fast for the Wetting Balance machine. For all the array of runs with an immersion speed of 25mm/sec, the run was repeated a number of times before the copper wires were immersed into the solder. The machine went into error mode at 25mm/sec because at this speed the machine is not capable of stopping at the small immersion depths. In order to prevent an occurrence of this error, the maximum speed for the detailed DoE will be set to 15mm/sec. 15mm/sec was determined by doing a trial on the Wetting Balance machine at high immersion speeds (up to 25mm/sec) to see what the optimum immersion speed was at such low immersion depths.

## Chapter 6 Theoretical Analysis of Wetting Balance Test

### 6.0 Introduction

From the results of the screening DoE in Chapter 5, it was concluded that two of the five factors, dwell time and removal speed, had no significant effect on any of the responses, Ta, Tb, Fmax, TFmax, F1 and F2. For this reason both of these factors were eliminated from any further investigation.

Also, when conducting the screening experiment it was noted that the immersion speed setting of 25mm/sec was too quick for the Wetting Balance machine to stop at the low immersion depths of between 3mm and 5mm. When the solder bath approached the test specimen at 25mm/sec, it was not capable of stopping at the required depths and went into error mode. On investigation, the maximum immersion speed setting capable of giving results at depths of between 3mm and 5mm was 15mm/sec. This figure would be thus used as the maximum setting. Using larger immersion depths of 10mm or more an immersion speed of 25mm/sec worked adequately. Table 6.1 shows the factors with minimum, intermediate and maximum settings that were used for DoE.

**Table 6.1 Factors and Settings for DoE2 – SN100C Alloy**

	<b>Minimum</b>	<b>Intermediate</b>	<b>Maximum</b>
<b>Factors</b>	<b>Value</b>	<b>Value</b>	<b>Value</b>
<b>Solder Temperature (°C)</b>	250	255	260
<b>Immersion Speed (mm/sec)</b>	5	10	15
<b>Immersion Depth (mm)</b>	3	4	5

In order to get an in-depth understanding of the effect the remaining three factors, solder temperature, immersion speed and immersion depth have on each of the responses, and to ensure accuracy for modelling purposes, a subsequent DoE will be carried out with a greater number of levels and run combinations. This gives rise to a full factorial DoE comprising of 27 runs with three replicates and for each run three repetitions resulting in 243 runs in total for the experiment. The average for each response was analysed with Minitab. Table 6.2 shows the array of runs designed by Minitab. Again the solder alloy used was SN100C and the test specimen a 0.9mm diameter copper wire pre-coated with the SN100C alloy prior to conducting each run. As stated in Chapter 3, the reason for this pre-coating was to reduce the effect of heat conduction of bare copper.

**Table 6.2 Experimental Run Structure**

RunOrder	Solder Temperature	Immersion Speed	Immersion Depth	RunOrder	Solder Temperature	Immersion Speed	Immersion Depth
1	255	5	5	42	255	5	3
2	260	5	4	43	250	10	4
3	255	10	4	44	255	15	3
4	255	15	5	45	255	10	5
5	260	5	3	46	260	15	3
6	255	15	3	47	255	15	3
7	250	15	3	48	250	10	3
8	250	10	4	49	250	15	5
9	255	10	3	50	260	5	5
10	260	15	4	51	260	5	4
11	250	10	3	52	260	5	3
12	255	10	5	53	255	15	5
13	255	15	4	54	260	10	4
14	260	5	4	55	255	15	5
15	260	5	3	56	255	10	4
16	260	10	5	57	255	10	4
17	260	10	3	58	250	15	5
18	255	15	4	59	255	5	4
19	260	10	4	60	255	10	3
20	260	15	3	61	260	5	5
21	250	10	5	62	250	15	4
22	255	5	4	63	250	15	5
23	260	15	4	64	255	5	4
24	260	15	5	65	250	5	5
25	255	15	4	66	260	15	5
26	260	15	4	67	260	10	3
27	250	5	5	68	255	5	5
28	250	10	4	69	250	15	4
29	260	10	4	70	250	15	3
30	250	5	4	71	250	10	3
31	250	10	5	72	250	5	4
32	250	15	3	73	250	10	5
33	250	15	4	74	250	5	3
34	255	5	3	75	250	5	3
35	250	5	4	76	255	5	3
36	255	10	5	77	260	10	3
37	260	10	5	78	250	5	3
38	255	10	3	79	255	5	5
39	260	15	3	80	260	15	5
40	250	5	5	81	260	5	5
41	260	10	5				

## 6.1 Analysis of Results

The Wetting Balance graphical results for each of the 243 runs are shown in Appendix 7. All of the results were analysed using Analysis of Variance (ANOVA) to determine the significant factors and interactions. A Main Effects graph and an Interaction graph will be used to assess the effects individually and also in combination with other affects respectively. The Main Effects graphs show the effect of each individual factor (solder temperature, immersion speed, immersion depth) for each response Ta, Tb, Fmax, TFmax, F1 and F2. The specification of each factor is stated along the x-axis for each graph. For the Interaction graphs, the effect between the combined factors for each of the responses is shown. There are two requirements to be achieved for each of the responses;

1. To get the optimum settings for each factor that will ensure the best possible result – this result will be used to develop the prediction model in order to have a value that can be verified against the requirement in point 2.
2. To determine the optimum settings for each factor that will ensure the worst possible result in terms of a Wetting Balance test. This result will ensure any components that are on the limit in terms of good / poor soldering ability will be detected during the Wetting Balance test.

### 6.1.1 Time to Buoyancy, Ta

An ANOVA table for Ta shows that individually solder temperature and immersion depth display significant effects, but the interaction between all three factors is also significant given that the p-values are less than 0.05.

**Table 6.3 ANOVA for Ta**

Analysis of Variance for Ta, using Adjusted SS for Tests					
Source	DF	Seq SS	Adj SS	Adj MS	F
Solder Temperature	2	0.087939	0.087939	0.043970	15.92
Immersion Speed	2	0.013105	0.013105	0.006552	2.37
Immersion Depth	2	0.023776	0.023776	0.011888	4.30
Solder Temperature*Immersion Speed	4	0.128632	0.128632	0.032158	11.64
Solder Temperature*Immersion Depth	4	0.033678	0.033678	0.008419	3.05
Immersion Speed*Immersion Depth	4	0.035983	0.035983	0.008996	3.26
Solder Temperature*Immersion Speed*Immersion Depth	8	0.054477	0.054477	0.006810	2.46
Error	54	0.149183	0.149183	0.002763	
Total	80	0.526772			
Source	P				
Solder Temperature	0.000				
Immersion Speed	0.103				
Immersion Depth	0.018				
Solder Temperature*Immersion Speed	0.000				
Solder Temperature*Immersion Depth	0.025				
Immersion Speed*Immersion Depth	0.018				
Solder Temperature*Immersion Speed*Immersion Depth	0.024				

It is also evident from Table 6.3 that the interaction between Solder Temperature - Immersion Speed, Solder Temperature - Immersion Depth, and Immersion Speed - Immersion Depth also display P-values less than 0.05. In order to evaluate the significance of these interactions the concept of Orthogonality was employed.

As a full factorial design was used it may be possible to eliminate some interactions thus making a more elegant model. Using the concept of Orthogonality this can be achieved. In any design of experiments the interaction terms are included however if these terms are independent of each other and independent of the other terms in the model it is possible to eliminate them from the model without having any effect on the response. This is called orthogonalisation and uses standard regression procedures. The big advantage of this



includes clarity of the model by eliminating any uninformative predictors (interaction terms) by reducing the full model to a simpler, less complicated, more elegant one.

When making a design of experiments every column in the design equates to a different factor and if every column in the design is orthogonal (independent of the others) then it's possible that every factor can be estimated independently from every other factor. This idea can then be applied to possibly eliminate all interaction factors and only have the main factors in the model.

From Table 6.3 above it is clear that some of the interactions are important but if these are removed from the model and the main effects are analysed as shown below the coefficients of the main effects remain unchanged. When this happens the interactions can be removed from the model and there will be no effect on the response. This is seen in Table 6.4 and comparisons between the two tables indicate that the model can be refined to eliminate the interactions as shown.

**Table 6.4 Orthogonality for Ta**

- $Ta = 2.35 - 0.00753 \text{ Solder Temperature (}^{\circ}\text{C)} + 0.00222 \text{ Immersion Speed (mm/sec)} + 0.0148 \text{ Immersion Depth (mm)} - 0.000183 A*B + 0.000138 A*C - 0.000946 B*C - 0.000119 A*B*C$

Predictor	Effect	Coef	SE	Coef	T	P
Constant		2.3526		0.002038	4.51	0.000
Solder Temperature (A) ( $^{\circ}\text{C}$ )	-0.1479	-0.007530	0.002038	-3.69	0.000	
Immersion Speed (B) (mm/sec)	0.0497	0.002219	0.002038	1.09	0.280	
Immersion Depth (C) (mm)	0.2847	0.014761	0.002038	1.45	0.152	
A*B	-0.0038	-0.000183	0.002038	-3.13	0.007	
A*C	0.0028	0.000138	0.002038	1.10	0.066	
B*C	-0.0018	-0.000946	0.002038	-2.03	0.035	
A*B*C	-0.0024	-0.000119	0.002038	-1.03	0.060	

S = 7.48874    R-Sq = 98.0%    R-Sq(adj) = 94.8%

The regression equation is

- $Ta = 2.35 - 0.00753 \text{ Solder Temperature (}^{\circ}\text{C)} + 0.00222 \text{ Immersion Speed (mm/sec)} + 0.0148 \text{ Immersion Depth (mm)}$

Predictor	Effect	Coef	SE	Coef	T	P
Constant		2.3526		0.002038	4.51	0.000
Solder Temperature (A) ( $^{\circ}\text{C}$ )	-0.1479	-0.007530	0.002038	-3.69	0.000	
Immersion Speed (B) (mm/sec)	0.0497	0.002219	0.002038	1.09	0.280	
Immersion Depth (C) (mm)	0.2847	0.014761	0.002038	1.45	0.152	

S = 11.48874    R-Sq = 78.0%    R-Sq(adj) = 84.8%

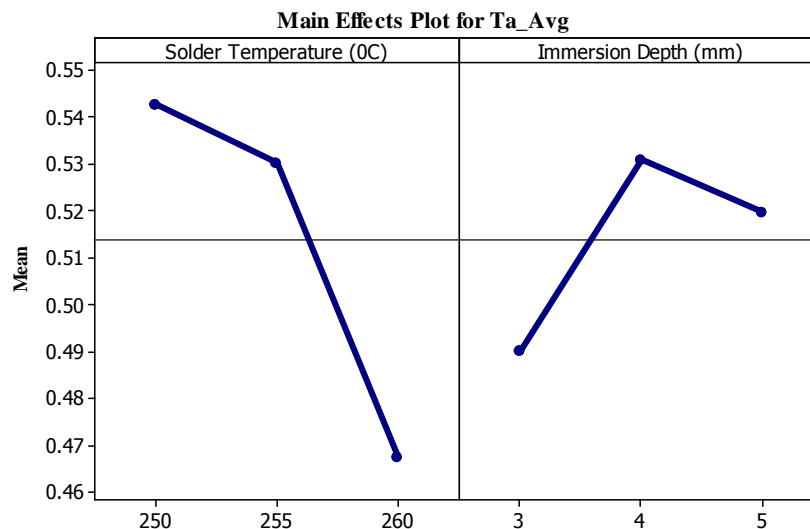
The Minitab analysis is shown in Table 6.4 and it indicates clearly when compared with Table 6.3 that as the coefficients of the main effects remain unchanged the interactions between Solder Temperature - Immersion Speed, Solder Temperature - Immersion Depth, and Immersion Speed - Immersion Depth can be removed from the model.

When the interaction are removed the refined model is as shown on at the middle of table 6.4 and this can easily be compared to the original model at the to of the table which contains the interaction effects.

Figure 6.1 is a Main Effects graph showing the two significant individual effects of the time to buoyancy. The specification requirement in the international standards states that Ta must be reached on or before 0.6 seconds, to give a good result.

Solder temperature and immersion depth are on the x-axis of the plot in Figure 6.1 and the mean values achieved for Ta in the experiment are listed on the y-axis. To assess the impact solder temperature (left of Figure 6.1) has on the time to buoyancy, Ta, it is evident from Figure 6.1 that the higher the temperature of the SN100C solder alloy enhances the chance of achieving the global specification,  $\leq 0.6$  seconds. At 250°C the average Ta is 0.54 seconds and at 260°C the average Ta result is 0.47 seconds. Having a fast Ta indicates good wetting of the solder wetting to the copper wire.

By focusing on the impact the immersion depth has on the time to buoyancy, a 3mm immersion depth (on the right x-axis) will give the shortest time of approximately 0.49 seconds (on the y-axis) to reach Ta and the longest time of approximately 0.53 seconds at a 4mm depth. At 5mm immersion depth the average Ta was 0.52 seconds. After review the results for 5mm immersion depth there were four outliers evident at Runs 37, 41, 61 and 81 that were caused by the an incorrect attachment of the copper wire in the holder. When these four outliers were removed the average Ta increased to 0.55 seconds.



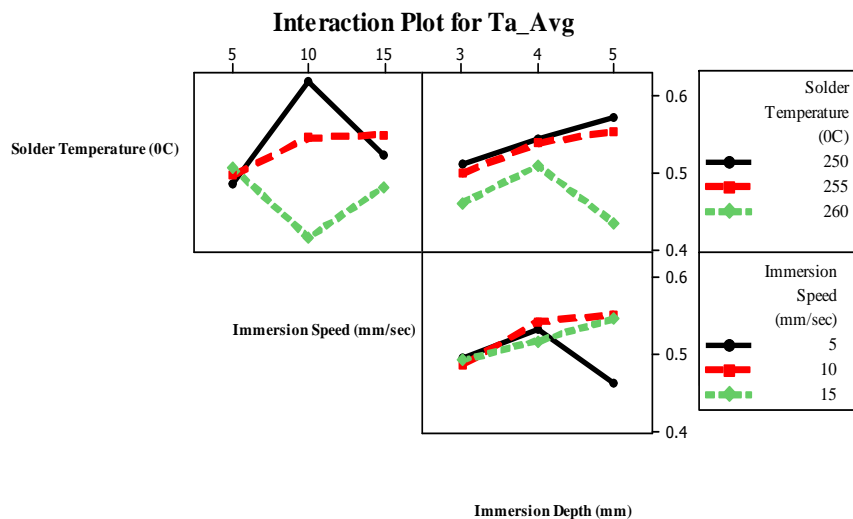
**Figure 6.1 Main Effects Graph for Ta (seconds)**

To get a more detailed understanding of the interactions between the three effects, solder temperature, immersion speed and immersion depth, Figure 6.2 shows an interaction graph that is discussed in Section 6.2.1.

#### 6.1.1.1 Correlation for Time to Buoyancy, Ta

It is apparent from the ANOVA table that there is correlation between the three factors and this is also evident from the interaction plot in Figure 6.2.

- Solder Temperature and Immersion Speed (square section on left side in Figure 6.2) – Maintaining an immersion speed of 10mm/sec and varying the solder temperatures between 250°C and 260°C increases the time to reach buoyancy from 0.41 seconds to 0.62 seconds respectively. At 250°C the 0.6 seconds specification limit is on average not achieved.
- Solder Temperature and Immersion Depth (square section on top right in Figure 6.2) – The correlation between solder temperature and immersion depth shows that the shortest Ta results are evident with a 3mm immersion depth. As mentioned earlier, there were four outliers evident at Runs 37, 41, 61 and 81. When these were removed the average Ta increased. At a 250°C solder temperature and with an immersion depth of 5mm give the longest time to reach buoyancy, thus the greater chance of a failure.



**Figure 6.2 Interaction Effects Graph for Ta (seconds)**

- Immersion Speed and Immersion Depth (square section on bottom right in Figure 6.2) – Again with the four outliers removed, varying the immersion depth between 3mm and 5mm and maintaining constant speeds of 5mm/sec, 10mm/sec and 15mm/sec increase the Ta value.

In summary a combination of a solder temperature at 260°C, an immersion speed at 15mm/sec and immersion depth at 3mm are optimum settings to achieve the Ta specification of  $\leq 0.6$  seconds as stated in the international standards. The lower temperature at 250°C, immersion speed at 15mm/sec and an immersion depth at 5mm give the longest result for Ta.

### 6.1.2 Time to cross the Zero Line, Tb

The ANOVA analysis in Table 6.5 shows that all factors and interactions between each of the factors are of significant importance. A global recognised specification of  $\leq 1$  second to cross the zero line is a requirement for all test specimens as stated in international standards.

**Table 6.5 ANOVA for Tb**

Analysis of Variance for Tb_Avg, using Adjusted SS for Tests					
Source	DF	Seq SS	Adj SS	Adj MS	F
Solder Temperature	2	0.087741	0.087741	0.043870	21.09
Immersion Speed	2	0.023241	0.023241	0.011620	5.59
Immersion Depth	2	0.050408	0.050408	0.025204	12.12
Solder Temperature*Immersion Speed	4	0.071366	0.071366	0.017842	8.58
Solder Temperature*Immersion Depth	4	0.029967	0.029967	0.007492	3.60
Immersion Speed*Immersion Depth	4	0.044232	0.044232	0.011058	5.32
Solder Temperature*Immersion Speed*Immersion Depth	8	0.049711	0.049711	0.006214	2.99
Error	54	0.112329	0.112329	0.002080	
Total	80	0.468994			
Source	P				
Solder Temperature	0.000				
Immersion Speed	0.006				
Immersion Depth	0.000				
Solder Temperature*Immersion Speed	0.000				
Solder Temperature*Immersion Depth	0.011				
Immersion Speed*Immersion Depth	0.001				
Solder Temperature*Immersion Speed*Immersion Depth	0.008				

Similar to Tb, there are interactions evident between Solder Temperature - Immersion Speed, Solder Temperature - Immersion Depth, and Immersion Speed – Immersion Depth. Using Orthogonality in Table 6.6 shows that these can be removed as they are all estimated independently.

**Table 6.6 Orthogonality for Tb**

- Tb = 2.44 - 0.00788 Solder Temperature (OC) + 0.00111 Immersion Speed (mm/sec) + 0.0284 Immersion Depth (mm) - 0.000091 A\*B + 0.000069 A\*C - 0.000047 B\*C + 0.000011 A\*B\*C**

Predictor	Effect	Coef	SE Coef	T	P
Constant		2.4363	0.001809	5.26	0.000
Solder Temperature (A) (OC)	-0.14567	-0.007878	0.001809	-4.36	0.000
Immersion Speed (B) (mm/sec)	0.02389	0.001115	0.001809	0.62	0.540
Immersion Depth (C) (mm)	0.50678	0.028352	0.001809	3.13	0.002
A*B	-0.00018	-0.000091	0.001809	-3.13	0.007
A*C	0.00013	0.000069	0.001809	1.10	0.066
B*C	-0.00094	-0.000047	0.001809	-2.03	0.035
A*B*C	0.00002	0.000011	0.001809	0.93	0.053

S = 6.64625    R-Sq = 97.5%    R-Sq(adj) = 94.7%

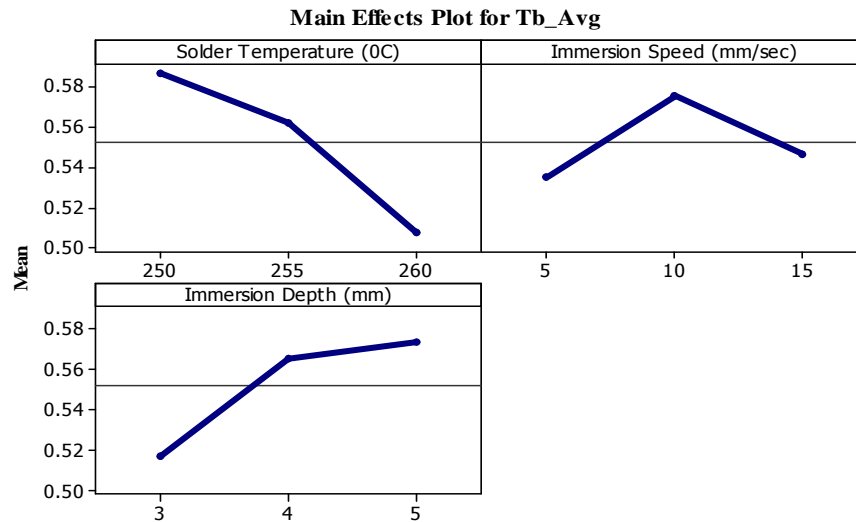
The regression equation is

- Tb = 2.44 - 0.00788 Solder Temperature (OC) + 0.00111 Immersion Speed (mm/sec) + 0.0284 Immersion Depth (mm)**

Predictor	Effect	Coef	SE Coef	T	P
Constant		2.4363	0.001809	5.26	0.000
Solder Temperature (OC)	-0.14567	-0.007878	0.001809	-4.36	0.000
Immersion Speed (mm/sec)	0.02389	0.001115	0.001809	0.62	0.540
Immersion Depth (mm)	0.50678	0.028352	0.001809	3.13	0.002

S = 10.97527    R-Sq = 77.5%    R-Sq(adj) = 84.6%

The Main Effects graph in Figure 6.3 shows very similar results for solder temperature to the results for  $T_a$  in Figure 6.1. A solder temperature of 260°C and an immersion depth of 3mm give a low  $T_a$  value. Again the immersion speed of 10mm/sec is showing signs of being an optimum speed setting for the Wetting Balance machine and this is further apparent in Figure 6.4, the interaction plot.

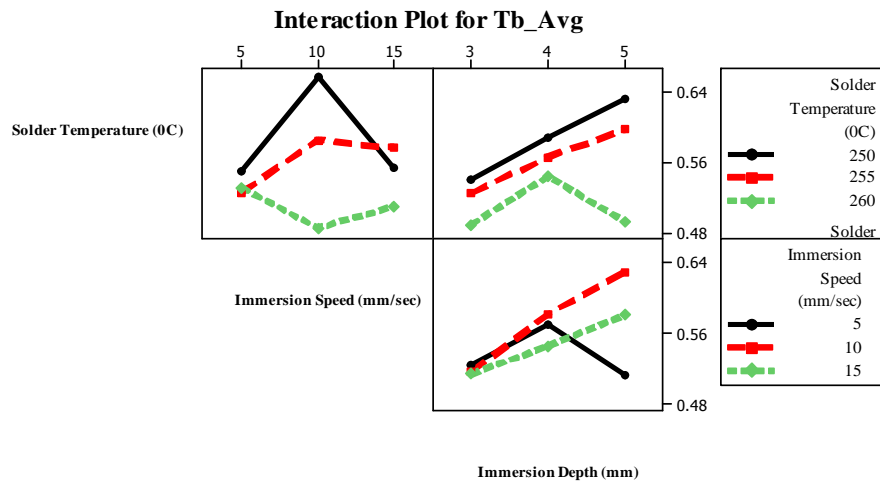


**Figure 6.3 Main Effects Graph for  $T_b$  (seconds)**

#### 6.1.2.1 Correlation for Time to reach Zero Line, $T_b$

The three main correlations for  $T_b$  are solder temperature and immersion speed, solder temperature and immersion depth and finally immersion speed and immersion depth. Similar to  $T_a$ , it is preferred to have  $T_b$  as short as possible. This indicates the speed at which solder wets the copper wire.

- Solder Temperature and Immersion Speed (left square section in Figure 6.4) – An immersion speed of 10mm/sec is the optimum setting in achieving a low and high value. In correlation with solder temperatures of 260°C and 250°C, a 10mm/sec immersion speed gives the shortest and longest times to reach the zero line respectively.
- Solder Temperature and Immersion Depth (right top square section in Figure 6.4) – The shortest times are achieved with 3mm immersion depths at 260°C (0.49 seconds) and at 250°C an immersion depth of 5mm gives the longest value (0.63 seconds).
- Immersion Speed and Immersion Depth (right bottom square section in Figure 6.4) – The most significant effect is apparent with constant speed of 10mm/sec and an immersion depth varying from 3mm to 5mm increasing the time from 0.52seconds to 0.63 seconds.



**Figure 6.4 Interaction Effects Graph for Tb (seconds)**

In summary, to achieve the optimum Tb reading (reading which meets the one second requirement), a solder temperature of 260°C, an immersion speed of 15mm/sec and an immersion depth of 3mm are required. The worst results are seen with a combination of the following; solder temperature at 250°C, immersion speed at 10mm/sec and immersion depth 5mm.

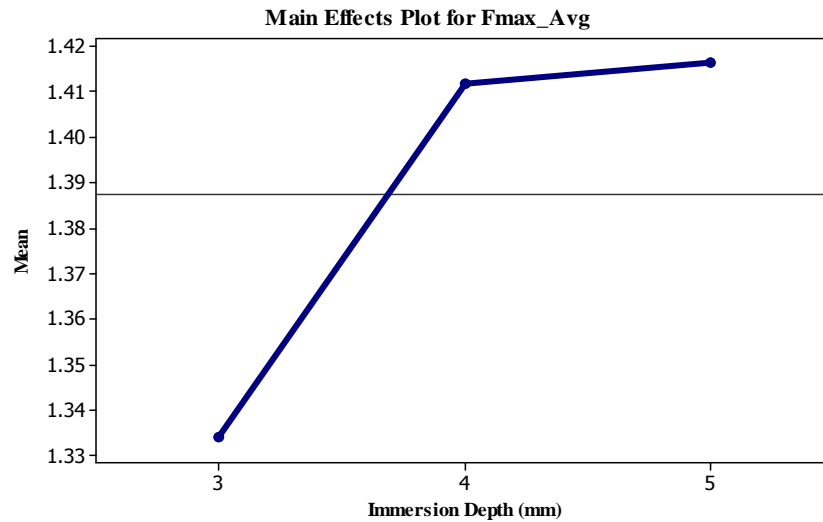
### 6.1.3 Maximum Force, Fmax

Immersion depth is the only factor that has a significant effect on the maximum force reached during the Wetting Balance test. No other correlation exists with the other two factors but with the p-value for the interaction relationship between immersion speed and immersion depth being 0.052, this will be considered for further analysis with an interaction graph.

**Table 6.7 ANOVA for Fmax**

Analysis of Variance for Fmax_Avg, using Adjusted SS for Tests						
Source	DF	Seq SS	Adj SS	Adj MS	F	
Solder Temperature	2	0.003782	0.003782	0.001891	1.23	
Immersion Speed	2	0.003441	0.003441	0.001720	1.12	
Immersion Depth	2	0.027971	0.027971	0.013985	9.10	
Solder Temperature*Immersion Speed	4	0.003786	0.003786	0.000947	0.62	
Solder Temperature*Immersion Depth	4	0.007399	0.007399	0.001850	1.20	
Immersion Speed*Immersion Depth	4	0.015450	0.015450	0.003862	2.51	
Solder Temperature*Immersion Speed*Immersion Depth	8	0.017199	0.017199	0.002150	1.40	
Error	54	0.082970	0.082970	0.001536		
Total	80	0.161999				
Source	P					
Solder Temperature	0.300					
Immersion Speed	0.334					
Immersion Depth	0.000					
Solder Temperature*Immersion Speed	0.653					
Solder Temperature*Immersion Depth	0.320					
Immersion Speed*Immersion Depth	0.052					
Solder Temperature*Immersion Speed*Immersion Depth	0.218					

The highest force result is achieved when a 5mm immersion depth is used as is evident in Figure 6.5. The theoretical expected value for a 0.9mm diameter copper wire immersed 4mm into an SN100C alloy is 1.24mN as calculated in Chapter 4. Figure 6.5 shows results that surpass this value, which indicate good solderability.

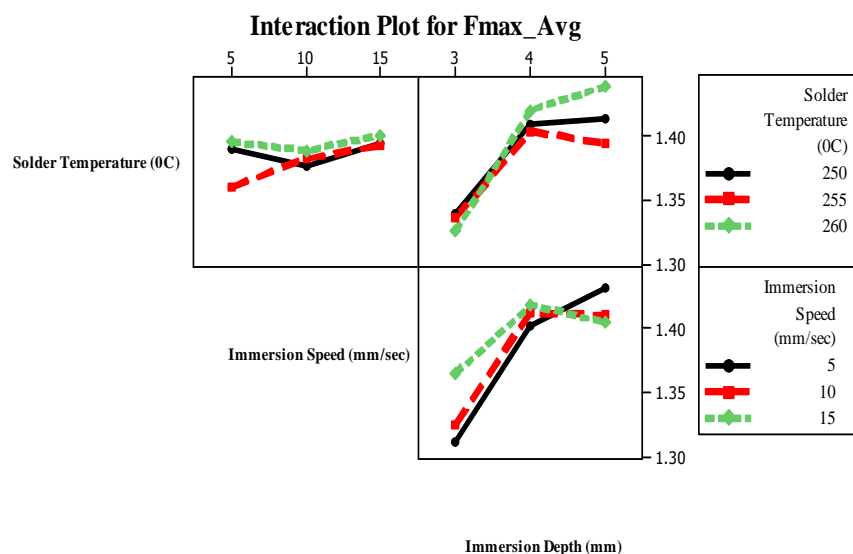


**Figure 6.5 Main Effects Graph for Fmax (mN)**

The higher the Fmax the better the solderability there is because the greater volume of solder on the test specimen pulling down on the component holder on the Wetting Balance machine.

### 6.1.3.1 Correlation for Maximum Force, Fmax

The correlation between immersion speed and immersion depth for Fmax is shown in Figure 6.6.



**Figure 6.6 Interaction Effects Graph for Fmax (mN)**

It was noted earlier that there were four outliers evident, caused by an incorrect mounting of the copper wire on the holder, at Runs 37, 41, 61 and 81 for the 5mm immersion depth. When these were again removed a reduction in Fmax was evident in Figure 6.6 at 5mm immersion depth was removed. Increasing the immersion depth from 3mm to 5mm increases the Fmax value at all three immersion speeds.

It can be concluded from the Fmax analysis that for an SN100C alloy an immersion speed of 5mm/sec and a 5mm immersion depth (bottom right square section) are optimum to achieve the highest possible Fmax result using a 0.9mm diameter copper wire. An immersion speed of 5mm/sec and an immersion depth of 3mm assist in reaching the lowest Fmax possible. Again as stated earlier this is due to the volume of solder wetting to the area of the copper wire immersed 3mm in contrast to 5mm.

#### 6.1.4 Time to reach Maximum Force, TFmax

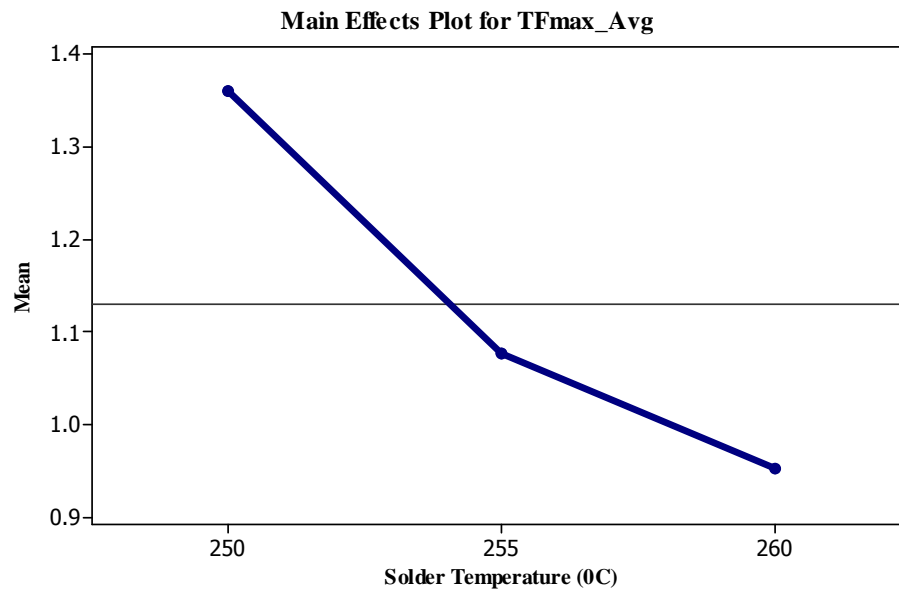
The requirement for TFmax is to reach the maximum force, Fmax, in the shortest time possible. From the array of runs that were experimented, only solder temperature had a significant effect as shown in the ANOVA table. All other factors were not included in any further analysis for TFmax.

**Table 6.8 ANOVA for TFmax**

Analysis of Variance for TFmax_Avg, using Adjusted SS for Tests					
Source	DF	Seq SS	Adj SS	Adj MS	F
Solder Temperature	2	2.35426	2.35426	1.17713	19.17
Immersion Speed	2	0.25535	0.25535	0.12768	2.08
Immersion Depth	2	0.05343	0.05343	0.02672	0.44
Solder Temperature*Immersion Speed	4	0.04925	0.04925	0.01231	0.20
Solder Temperature*Immersion Depth	4	0.18347	0.18347	0.04587	0.75
Immersion Speed*Immersion Depth	4	0.13517	0.13517	0.03379	0.55
Solder Temperature*Immersion Speed*Immersion Depth	8	0.34412	0.34412	0.04302	0.70
Error	54	3.31610	3.31610	0.06141	
Total	80	6.69116			
Source	P				
Solder Temperature	0.000				
Immersion Speed	0.135				
Immersion Depth	0.649				
Solder Temperature*Immersion Speed	0.937				
Solder Temperature*Immersion Depth	0.564				
Immersion Speed*Immersion Depth	0.700				
Solder Temperature*Immersion Speed*Immersion Depth	0.690				

The Main Effects graph in Figure 6.7 for TFmax indicates that the best result, the fastest time, is achieved with a 260°C solder temperature for an SN100C alloy. The cooler solder temperature the longer the time to reach Fmax. The higher solder temperature increases the viscosity of the solder thus creating better fluidity for the solder to flow when it has a good surface area to wet to such as the copper wire.





**Figure 6.7 Main Effects Graph for TFmax (seconds)**

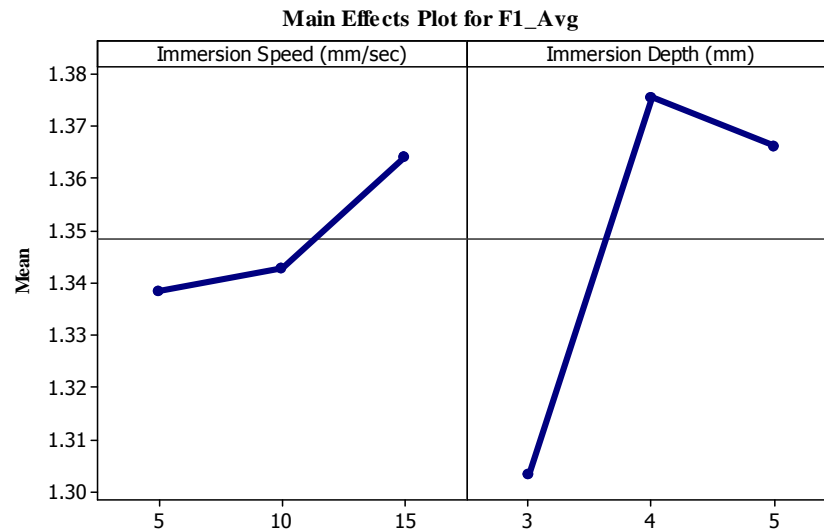
### 6.1.5 Force at two seconds, F1

The globally recognised requirement for the force at two seconds is no less than 50% Fmax. In this case the theoretical Fmax is 1.42mN giving a theoretical F1 value of 0.71mN.

**Table 6.9 ANOVA for F1**

Analysis of Variance for F1_Avg, using Adjusted SS for Tests					
Source	DF	Seq SS	Adj SS	Adj MS	F
Solder Temperature	2	0.007387	0.007387	0.003694	2.36
Immersion Speed	2	0.010229	0.010229	0.005115	3.27
Immersion Depth	2	0.083323	0.083323	0.041661	26.63
Solder Temperature*Immersion Speed	4	0.007638	0.007638	0.001910	1.22
Solder Temperature*Immersion Depth	4	0.007505	0.007505	0.001876	1.20
Immersion Speed*Immersion Depth	4	0.007562	0.007562	0.001891	1.21
Solder Temperature*Immersion Speed*Immersion Depth	8	0.022026	0.022026	0.002753	1.76
Error	54	0.084484	0.084484	0.001565	
Total	80	0.230153			
Source	P				
Solder Temperature	0.104				
Immersion Speed	0.046				
Immersion Depth	0.000				
Solder Temperature*Immersion Speed	0.313				
Solder Temperature*Immersion Depth	0.322				
Immersion Speed*Immersion Depth	0.318				
Solder Temperature*Immersion Speed*Immersion Depth	0.106				

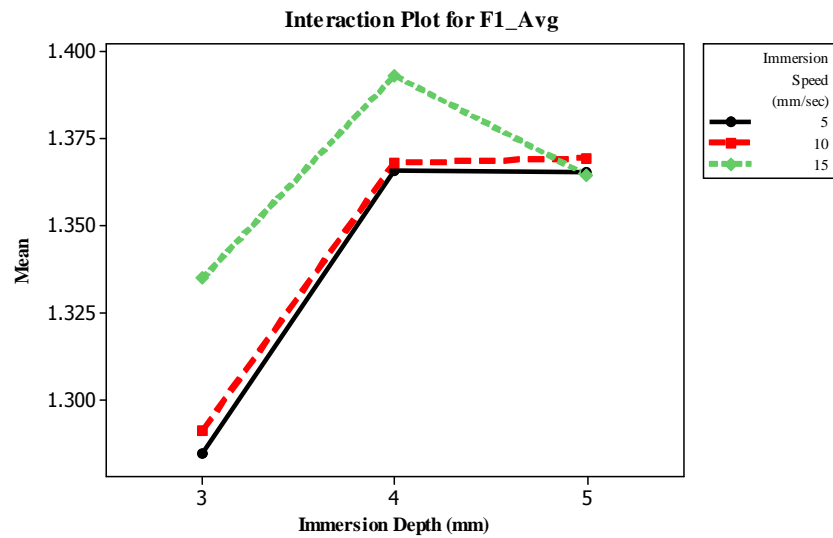
From the ANOVA analysis, immersion speed and immersion depth are the only factors that have an effect on F1. It is evident from the Main Effects graph in Figure 6.8 that an immersion speed of 15mm/sec gives the highest F1 value. For immersion depth there is a significant increase from 3mm to 4mm but when using the 5mm depth the F1 value is reduced. It is preferred to have the force measurement as high as possible which indicates the high volume of solder wetted to the copper wire.



**Figure 6.8 Main Effects Graph for F1 (mN)**

#### 6.1.5.1 Correlation for Force at 2 seconds, F1

From Figure 6.9 the correlation between immersion speed and immersion depth is evident. There is no correlation with solder temperature for F1.



**Figure 6.9 Interaction Effects Graph for F1 (mN)**

The largest force value is achieved with an immersion speed of 15mm/sec and an immersion depth of 4mm. With an immersion depth of 3mm and an immersion speed of 5mm/sec the lowest reading for the force at two seconds is evident.

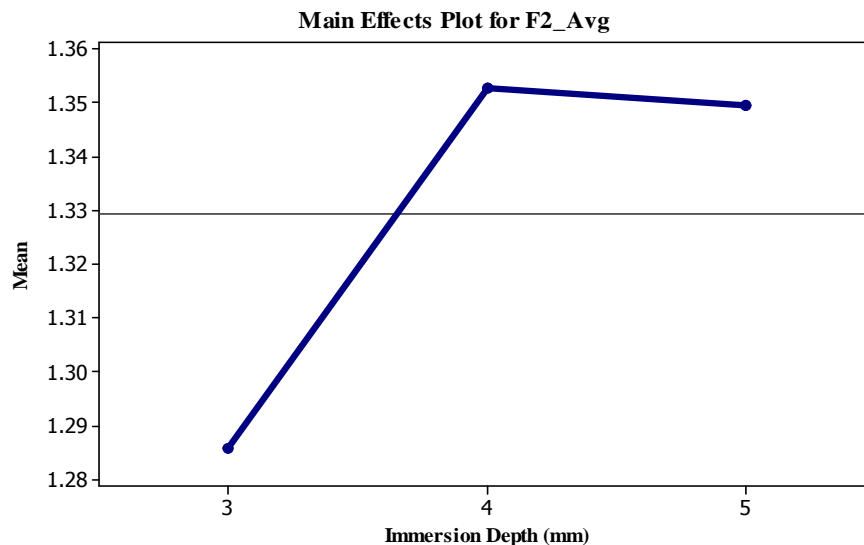
#### 6.1.6 Force at five seconds, F2

Again using the ANOVA with Minitab to analyse the force achieved at five seconds (F2) of the Wetting Balance test shows only immersion depth has a significant effect.

**Table 6.10 ANOVA for F2**

Analysis of Variance for F2_Avg, using Adjusted SS for Tests					
Source	DF	Seq SS	Adj SS	Adj MS	F
Solder Temperature	2	0.009542	0.009542	0.004771	2.49
Immersion Speed	2	0.004935	0.004935	0.002467	1.29
Immersion Depth	2	0.077595	0.077595	0.038797	20.26
Solder Temperature*Immersion Speed	4	0.008691	0.008691	0.002173	1.13
Solder Temperature*Immersion Depth	4	0.010754	0.010754	0.002688	1.40
Immersion Speed*Immersion Depth	4	0.008079	0.008079	0.002020	1.05
Solder Temperature*Immersion Speed*Immersion Depth	8	0.028524	0.028524	0.003565	1.86
Error	54	0.103406	0.103406	0.001915	
Total	80	0.251524			
Source	P				
Solder Temperature	0.092				
Immersion Speed	0.284				
Immersion Depth	0.000				
Solder Temperature*Immersion Speed	0.350				
Solder Temperature*Immersion Depth	0.245				
Immersion Speed*Immersion Depth	0.388				
Solder Temperature*Immersion Speed*Immersion Depth	0.085				

The Main Effects graph in Figure 6.10 for the force reached at five seconds in terms of the immersion depth shows a similar reading to what was seen for F1. From a 3mm to 4mm depth there is a significant increase in force reading but at a 5mm depth the force reading decreases.

**Figure 6.10 Main Effects Graph for F2 (mN)**

## 6.2 Conclusions from Experiment

In Chapter 5 a screening experiment showed that only three factors, solder temperature, immersion speed and immersion depth, had effects on the five responses, Ta, Tb, Fmax, TFmax, F1 and F2. In this chapter a more detailed in-depth DoE was carried out with the three factors each with three levels. The objectives were to obtain the optimum settings that would achieve the least and most stringent settings. This would allow one to understand the impact of testing components at the upper and lower levels of each factor,

solder temperature, immersion speed and immersion depth, as per the international standards. It would also aid in assisting the Wetting Balance user to decide what side of the specification to test at, for example solder temperature of 250°C versus 260°C. The investigation so far has indicated that the higher temperature of 260°C helps in achieving good solderability. Table 6.11 shows the optimum settings for all responses in achieving these objectives.

From Table 6.11 the Ta, Tb and TFmax optimum settings for the least and most stringent soldering settings are identical and can therefore be grouped. Similarly, both F1 and F2 can be grouped and finally Fmax will be analysed separately. What we now have in Table 6.11 are settings that show how running the Wetting Balance machine at the lower end of the specification as opposed to the higher end can influence the outcome. It is important for the component user to understand this when testing suspect components on a Wetting Balance machine.

**Table 6.11 Summary of Optimum Settings**

<u>Responses</u>	<u>Factors</u>	<u>Least Stringent</u>	<u>Most Stringent</u>
Ta	Solder Temperature	260°C	250°C
	Immersion Speed	15mm/sec	10mm/sec
	Immersion Depth	3mm	5mm
Tb	Solder Temperature	260°C	250°C
	Immersion Speed	15mm/sec	10mm/sec
	Immersion Depth	3mm	5mm
TFmax	Solder Temperature	260°C	250°C
	Immersion Speed	Not Significant	Not Significant
	Immersion Depth	Not Significant	Not Significant
Fmax	Solder Temperature	Not Significant	Not Significant
	Immersion Speed	5mm/sec	5mm/sec
	Immersion Depth	5mm	3mm
F1	Solder Temperature	Not Significant	Not Significant
	Immersion Speed	15mm/sec	5mm/sec
	Immersion Depth	4mm	3mm
F2	Solder Temperature	Not Significant	Not Significant
	Immersion Speed	Not Significant	Not Significant
	Immersion Depth	4	3

## Chapter 7 Model Generation and Numerical Analysis

### 7.0 Introduction

Chapter 6 provided an in-depth DoE for each of the responses, Ta, Tb, Fmax, TFmax, F1 and F2 and from it presented two groups of settings for each response. The least stringent settings would give the test specimens the best possible situation to assist in soldering and the most stringent settings would provide the worst possible situation for soldering with the Wetting Balance machine. It was concluded after the analysis that Ta and Tb each had similar optimum settings for least stringent and most stringent soldering ability and therefore grouped together with TFmax. The other two groups were F1 with F2, and finally Fmax. The settings for each factor are shown in Tables 7.1 and 7.2 and these will be used to verify the model equations.

This chapter suggests mathematical models that best describe the effects of the selected Wetting Balance machine variables, solder temperature, immersion speed and immersion depth. These model equations (Equation 7.00, 7.01, 7.02, 7.03, 7.04, 7.05) will afford the user of the Wetting balance machine predictable test results for each of the responses, Ta, Tb, Fmax, TFmax, F1 and F2, based on the solder temperature, immersion speed and immersion depth parameter settings used on the MUST II machine. As mentioned earlier, there are specification requirements for Ta (less than 0.6 seconds), Tb (Less than 1 second), F1 (no less than 50% of Fmax) and F2 (no less than 90% of F1). There is currently no acceptable criterion for Fmax or TFmax. The investigations in Chapter 6 have shown the difference evident in the results for each of the responses when testing at different end of the parameter specifications by the use of Main Effect and Interaction graphs. This chapter will explore these differences in more detail by the use of mathematical models and actual test results from the Wetting Balance machine.

The model equations generated by Minitab will be compared with the actual results by inputting the solder temperature, immersion speed and immersion depth values from Tables 7.1 and 7.2 into the Wetting Balance machine and conducting tests. The actual readings will be achieved by conducting experiments using the Wetting Balance machine. All data presented refers to a MUST II Wetting Balance machine with a SN100C alloy, and a 0.9mm diameter copper wire. Similar to all previous testing using the copper wire, a double dip was used to eliminate the heat conduction of copper that is evident when soldering onto bare copper.

The slope (m) of the resulting Wetting Balance graphs will also be assessed to determine what, if any, affect it may have on the results for each of the responses.

**Table 7.1 Optimum Parameter settings – Least Stringent Settings**

Responses	Factors		
	Solder Temperature (°C)	Immersion Speed (mm/sec)	Immersion Depth (mm)
<b>Ta / Tb</b>	260	15	3
<b>TFmax</b>	260	15*	4*
<b>Fmax</b>	260*	5	5
<b>F1</b>	260*	15	4
<b>F2</b>	260*	15*	4

The asterisk (\*) in Tables 7.1 and 7.2 indicate that that settings will be used even though they are not significant for that response. Take an example in Table 7.1: 260°C will be used for Fmax, TFmax, F1 and F2 even though solder temperature has no significant effect on each of these responses. However it will reduce the amount of testing in the DoE.

**Table 7.2 Optimum Parameter settings – Most Stringent Settings**

Responses	Factors		
	Solder Temperature (°C)	Immersion Speed (mm/sec)	Immersion Depth (mm)
<b>Ta / Tb</b>	250	10	5
<b>TFmax</b>	250	5*	3*
<b>Fmax</b>	250*	5	3
<b>F1</b>	250*	5	3
<b>F2</b>	250*	5*	3

## 7.1 Regression and Model Equation Generation

Using the appropriate variables, solder temperature, immersion speed and immersion depth, a regression equation was generated by Minitab for each of the responses Ta, Tb, Fmax, TFmax, F1 and F2 using the results from DoE2 in Chapter 6. These regression equations are the basis for this research and for the Wetting Balance machine. They are based on extensive testing using a full factorial design of experiments comprising of 27 runs with three replicates and for each run three repetitions resulting in 243 runs in total. The graphical representations for each run are available in Appendix 8. These equations represent the ‘predicted’ values expected when using the different parameter settings for solder temperature, immersion speed and immersion depth when using the Wetting

Balance machine. The regression equations developed by Minitab using the results from 243 runs are:

$$Ta_{\text{predicted}} = C - 0.00753 T_s + 0.00222 I_s + 0.0148 I_D \quad \dots \text{Eq-7.00}$$

Where C is a constant 2.35

$$Tb_{\text{predicted}} = C - 0.00788 T_s + 0.00111 I_s + 0.0284 I_D \quad \dots \text{Eq-7.01}$$

Where C is a constant 2.44

$$F_{\text{max}} = C + 0.00142 I_s - 0.0413 I_D \quad \dots \text{Eq-7.02}$$

Where C is a constant 1.21

$$TF_{\text{max}_{\text{predicted}}} = C - 0.00427 I_s + 0.0312 I_D \quad \dots \text{Eq-7.03}$$

Where C is a constant 1.05

$$F1_{\text{predicted}} = C + 0.00257 I_s + 0.0315 I_D \quad \dots \text{Eq-7.04}$$

Where C is a constant 1.20

$$F2_{\text{predicted}} = C + 0.0320 I_D \quad \dots \text{Eq-7.05}$$

Where C is a constant 1.20

Where:  $T_s$  = Solder Temperature ( $^{\circ}\text{C}$ )

$I_s$  = Immersion Speed (mm/sec)

$I_D$  = Immersion Depth (mm)

C = Constant

Where appropriate the factors that were not significant for the responses were ignored when developing the model equations. The constants for each equation were automatically calculated by Minitab and are denoted by the letter 'C' in each case. Minitab develops the predicted questions using only the absolute values and calculates the equations ignoring these units. For example it is similar to Time v Solder Temperature in a Wave Soldering profile, which give a solder joint strength of 10N while at a different Time, and Solder Temperature gives a solder joint strength of 2N. These are just factors and the response is measured in Newton's. A similar theory applies in the case of the model equations 7.00 to 7.05. It is important to ensure the correct units are used for the main variables when using the Wetting Balance machine.

## 7.2 Regression Equation Analysis

To test the accuracy of the equations 7.00 to 7.05, the ‘actual’ results will be calculated for each response by using the parameter settings from Tables 7.1 and 7.2. These settings will be then tested in the Wetting Balance machine to compare the ‘predicted’ optimum least stringent and ‘predicted’ optimum most stringent soldering results using the equations 7.00 to 7.05 with the actual results got by conducting the DoE later in the chapter.

### 7.2.1 Regression Equation, Ta

The regression equation for Ta developed by Minitab is:

$$Ta_{\text{predicted}} = C - 0.00753 T_s + 0.00222 I_s + 0.0148 I_D \quad \dots \text{Eq-7.00}$$

The optimum least settings from Table 7.1 for Ta are:

- Solder Temperature – 260°C
- Immersion Speed – 15mm/sec
- Immersion Depth – 3mm

Using these settings the Equation 7.00 now becomes:

$$\begin{aligned} Ta_{\text{predicted}} &= C - 0.00753 T_s + 0.00222 I_s + 0.0148 I_D \\ Ta_{\text{predicted}} &= 2.35 - (0.0753 \times 260) + (0.00222 \times 15) + (0.0148 \times 3) \quad \dots \text{Eq-7.06} \\ Ta_{\text{predicted}} &= 0.4699 = 0.47 \text{ sec} \end{aligned}$$

A 0.47 second time to buoyancy is the ‘predicted’ value (least stringent) that can be achieved when using a 0.9mm diameter copper wire in SN100C solder. To determine the predicted most stringent value for time to buoyancy the following settings are used from Table 7.2.

- Solder Temperature – 250°C
- Immersion Speed – 10mm/sec
- Immersion Depth – 5mm

The  $Ta_{\text{predicted}}$  equation now becomes:

$$\begin{aligned} Ta_{\text{predicted}} &= C - 0.00753 T_s + 0.00222 I_s + 0.0148 I_D \\ Ta_{\text{predicted}} &= 2.35 - (0.0753 \times 250) + (0.00222 \times 10) + (0.0148 \times 5) \quad \dots \text{Eq-7.07} \\ Ta_{\text{predicted}} &= 0.5637 = 0.56 \text{ sec} \end{aligned}$$

The predicted values for time to buoyancy, Ta, using the model Equation 7.00 are as follows:



- 0.47 seconds result for Ta (least stringent)
- 0.56 seconds for Ta (most stringent)

### 7.2.2 Regression Equation, Tb

The regression equation developed by Minitab for Tb is:

$$Tb_{\text{predicted}} = C - 0.00788 T_s + 0.00111 I_s + 0.0284 I_D \quad \dots \text{Eq-7.01}$$

The optimum settings from Table 7.1 for Tb are the same used for Ta:

- Solder Temperature – 260°C
- Immersion Speed – 15mm/sec
- Immersion Depth – 3mm

The Tb<sub>predicted</sub> equation now becomes:

$$\begin{aligned} Tb_{\text{predicted}} &= C - 0.00788 T_s + 0.0011 I_s + 0.0284 I_D \\ Tb_{\text{predicted}} &= 2.44 - (0.0788 \times 260) + (0.0011 \times 15) + (0.0284 \times 3) \quad \dots \text{Eq-7.08} \\ Tb_{\text{predicted}} &= 0.49305 = 0.49 \text{ sec} \end{aligned}$$

The most stringent settings used to obtain the soldering value for time to cross the zero line (Tb) are:

- Solder Temperature – 250°C
- Immersion Speed – 10mm/sec
- Immersion Depth – 5mm

The Tb<sub>predicted</sub> equation now becomes:

$$\begin{aligned} Tb_{\text{predicted}} &= C - 0.00788 T_s + 0.0011 I_s + 0.0284 I_D \\ Tb_{\text{predicted}} &= 2.44 - (0.0788 \times 250) + (0.0011 \times 10) + (0.0284 \times 5) \quad \dots \text{Eq-7.09} \\ Tb_{\text{predicted}} &= 0.6231 = 0.62 \text{ sec} \end{aligned}$$

The predicted values, using model Equations 7.01, are as follows for time to cross the zero line, Tb, on the Wetting Balance machine are:

- 0.49 seconds for Tb (least stringent)
- 0.62 seconds for Tb (most stringent)

### 7.2.3 Regression Equation, Fmax

The regression equation for maximum force, Fmax, is stated in Equation 7.02. The asterisk signifies that the factor (solder temperature) is not significant for the response. This was determined in Chapter 6.

$$F_{\text{max}_{\text{predicted}}} = C + 0.00142 I_s - 0.0413 I_D \quad \dots \text{Eq-7.02}$$

The optimum settings from Table 7.1 for Fmax are:

- Solder Temperature – 260°C\*
- Immersion Speed – 5mm/sec
- Immersion Depth – 5mm

The equation now becomes:

$$\begin{aligned} F_{\text{max}_{\text{predicted}}} &= C + 0.00142 I_s - 0.0413 I_D \\ F_{\text{max}_{\text{predicted}}} &= 1.21 + (0.00142 \times 5) - (0.0413 \times 5) \quad \dots \text{Eq-7.10} \\ F_{\text{max}_{\text{predicted}}} &= 1.0932 = 1.09\text{mN} \end{aligned}$$

From Table 7.2 the settings used for Fmax are:

- Solder Temperature – 250°C\*
- Immersion Speed – 5mm/sec
- Immersion Depth – 3mm

The equation now becomes:

$$\begin{aligned} F_{\text{max}_{\text{predicted}}} &= C + 0.00142 I_s - 0.0413 I_D \\ F_{\text{max}_{\text{predicted}}} &= 1.21 + (0.00142 \times 5) - (0.0413 \times 3) \quad \dots \text{Eq-7.11} \\ F_{\text{max}_{\text{predicted}}} &= 1.0106 = 1.01\text{mN} \end{aligned}$$

In summary the predicted values for the maximum force, Fmax, using model Equations 7.02 are as follows:

- 1.09mN for Fmax (least stringent)
- 1.01mN for Fmax (most stringent)

### 7.2.4 Regression Equation, TFmax

Based on the Fmax results the time to reach the maximum force, TFmax, is calculated using the regression Equation 7.03.

$$TF_{\text{max}_{\text{predicted}}} = C - 0.00427 I_s + 0.0312 I_D \quad \dots \text{Eq-7.03}$$

From Table 7.1 the optimum settings for TFmax are:

- Solder Temperature – 260°C\*
- Immersion Speed – 15mm/sec
- Immersion Depth – 3mm

The Equation 7.03 now becomes:

$$\begin{aligned} \text{TFmax}_{\text{predicted}} &= C - 0.00427 I_s + 0.0312 I_D \\ \text{TFmax}_{\text{predicted}} &= 1.05 - 0.00427 (15) + 0.0312 (3) \quad \dots \text{Eq-7.11} \\ \text{TFmax}_{\text{predicted}} &= 1.07955 = 1.08 \text{sec} \end{aligned}$$

The settings from Table 7.2 for TFmax are:

- Solder Temperature – 250°C\*
- Immersion Speed – 10mm/sec
- Immersion Depth – 5mm

The Equation 7.03 now becomes:

$$\begin{aligned} \text{TFmax}_{\text{predicted}} &= C - 0.00427 I_s + 0.0312 I_D \\ \text{TFmax}_{\text{predicted}} &= 1.05 - 0.00427 (10) + 0.0312 (5) \quad \dots \text{Eq-7.12} \\ \text{TFmax}_{\text{predicted}} &= 1.1633 = 1.16 \text{sec} \end{aligned}$$

In summary the predicted values for time to reach the maximum force, TFmax, using model Equation 7.03 are as follows:

- 1.08 seconds for TFmax (least stringent)
- 1.16 seconds for TFmax (most stringent)

### **7.2.5 Regression Equation, F1**

The regression equation developed by Minitab for the force reached at two seconds is:

$$F1_{\text{predicted}} = C + 0.00257 I_s + 0.0315 I_D \quad \dots \text{Eq-7.04}$$

Using the settings from Table 7.1:

- Solder Temperature – 260°C\*
- Immersion Speed – 15mm/sec
- Immersion Depth – 4mm

Equation 7.04 now becomes:

$$\begin{aligned}F1_{\text{predicted}} &= C + 0.00257I_S + 0.0315 I_D \\F1_{\text{predicted}} &= 1.20 + 0.00257(15) + 0.0315 (4) \\F1_{\text{predicted}} &= 1.3298\text{mN} = 1.33\text{mN}\end{aligned}\quad \dots\text{Eq-7.13}$$

To obtain the most stringent optimum value for F1 using the parameter settings from Table 7.1:

- Solder Temperature – 250°C\*
- Immersion Speed – 5mm/sec
- Immersion Depth – 3mm

Equation 7.04 now becomes:

$$\begin{aligned}F1_{\text{predicted}} &= C + 0.00257I_S + 0.0315 I_D \\F1_{\text{predicted}} &= 1.20 + 0.00257(5) + 0.0315 (3) \\F1_{\text{predicted}} &= 1.3073\text{mN} = 1.31\text{mN}\end{aligned}\quad \dots\text{Eq-7.14}$$

In summary the predicted values are as follows:

- 1.33mN for F1 (least stringent)
- 1.31mN for F1 (most stringent)

### 7.2.6 Regression Equation, F2

Like the previous equations, Equation 7.05 was generated by Minitab based on the results obtained from the DoE in Chapter 6.

$$F2_{\text{predicted}} = C + 0.0320 I_D \quad \dots\text{Eq-7.05}$$

Using the setting from Table 7.1:

- Solder Temperature – 260°C\*
- Immersion Speed – 15mm/sec\*
- Immersion Depth – 4mm

Equation 7.05 now becomes:

$$\begin{aligned}F2_{\text{predicted}} &= C + 0.0320 I_D \\F2_{\text{predicted}} &= 1.20 + 0.0320 (4) \\F2_{\text{predicted}} &= 1.328 = 1.33\text{mN}\end{aligned}\quad \dots\text{Eq-7.15}$$

The settings from Table 7.2 for the predicted F2 were:

- Solder Temperature – 250°C\*

- Immersion Speed – 5mm/sec\*
- Immersion Depth – 3mm

Equation 7.05 now becomes:

$$\begin{aligned}F2_{\text{predicted}} &= C + 0.0320 I_D \\F2_{\text{predicted}} &= 1.20 + 0.0320 (3) \\F2_{\text{predicted}} &= 1.296 = 1.30\text{mN}\end{aligned}\quad \dots\text{Eq-7.16}$$

In summary the predicted values are as follows:

- 1.33mN for F2 (least stringent)
- 1.30mN for F2 (most stringent)

### 7.2.7 Conclusions from Regression Equations

After concluding the analysis for each regression equation, both the ‘predicted’ results for the least and most stringent settings were determined by using the settings from the Tables 7.1 and 7.2. Table 7.3 is a summary of the predicted values for each of the responses obtained by using the Equations 7.00 to 7.05.

**Table 7.3 Overview of Predicted Response Values**

Responses	Least	Most
	Stringent	Stringent
Ta (seconds)	0.47	0.56
Tb (seconds)	0.49	0.62
Fmax (mN)	1.09	1.01
TFmax (seconds)	1.08	1.16
F1 (mN)	1.33	1.31
F2 (mN)	1.33	1.30

There is now the possibility to have upper and lower limit specifications on each of the responses using a 0.9mm diameter copper wire pre-coated with SN100C alloy. Within the International Standards the specification limit for Ta ( $\leq 0.6$  seconds) and Tb ( $\leq 1$  second) are too large. Similarly for F1 and F2 the current criteria for these are ‘not less than 50% of Fmax’ and ‘no less than 90% of F1’ respectively and from experience these are easily achieved even for components with very poor soldering ability. The specification limits on all these responses must be to a minimum in order to screen poor soldering components.

### 7.3 Regression Equation Verification

In order to assess the predicted response values from Table 7.3, experimental runs were carried out using the optimum settings for both soldering conditions, least and most stringent. Figures 7.1, 7.2, 7.3, 7.4, 7.5 and 7.6 show the graphical results from the Wetting Balance machine. Again similar to the previous DoE's throughout this project, 0.9mm diameter copper wires were used as the test specimens and the alloy used was SN100C.

#### 7.3.1 Regression Equation Verification for Ta, Tb, and TFmax

As stated earlier in the chapter, Ta, Tb and TFmax were grouped together because they had similar settings as a result of the analysis in Chapter 6. Figure 7.1 shows the Wetting Balance graph for the least stringent optimum settings for the responses Ta, Tb and TFmax from Table 7.1. These significant settings were as follows:

**Table 7.4 Least Stringent settings for Ta, Tb and TFmax**

Responses	Factors		
	Solder Temperature (°C)	Immersion Speed (mm/sec)	Immersion Depth (mm)
<b>Ta / Tb (seconds)</b>	260	15	3
<b>TFmax (mN)</b>	260	15*	3*

The analysis in Chapter 6 has shown for Ta and Tb, solder temperature, immersion speed and immersion depth had significant effects. However, for TFmax, only solder temperature had an effect so the impact of immersion speed and immersion depth would not affect the result.

In Section 2.4.5 Figure 2.22, a detailed explanation of the Wetting Balance graph was analysed. From point 2, when the test specimen has reached soldering temperature, to point 4, when the test specimen has reached the x-axis on the Wetting Balance graph, the slope (m) of the line will be assessed to determine if there is any relationship apparent using the formula:

$$\frac{Y_2 - Y_1}{X_2 - X_1} \quad \dots \text{Eq-7.17 [86]}$$

Where X1, X2, Y1, Y2 are co-ordinates from a line on the Wetting Balance graph. These co-ordinates were obtained using a software package, MUST II +, from the machine supplier. A high slope (m) would indicate good wetting of the component lead because the speed of wetting would be short. Using Equation 7.17 the slope was calculated as:

$$\frac{1.2 - (-0.95)}{1.2 - 1.0} = \frac{2.15}{0.2} = 10.75$$

This value would indicate a good wetting characteristic and will be compared with other calculated slopes. This result is based on the optimum least stringent settings, which provide the best possible soldering conditions from the Wetting Balance machine to encourage wetting of the solder to the test specimen. The average, range and standard deviations of the five readings from Figure 7.1 was calculated as shown:

0.459, 0.393, 0.447, 0.414, 0.378

Average = 0.42 seconds

Range = 0.081

= 0.035

0.471, 0.405, 0.462, 0.429, 0.393

Average = 0.43 seconds

Range = 0.078

= 0.034

0.750, 0.642, 0.708, 0.681, 0.615

Average = 0.679 = 0.68 seconds

Range = 0.135

= 0.113

- Ta Actual:

- Tb Actual:

- TFmax Actual:

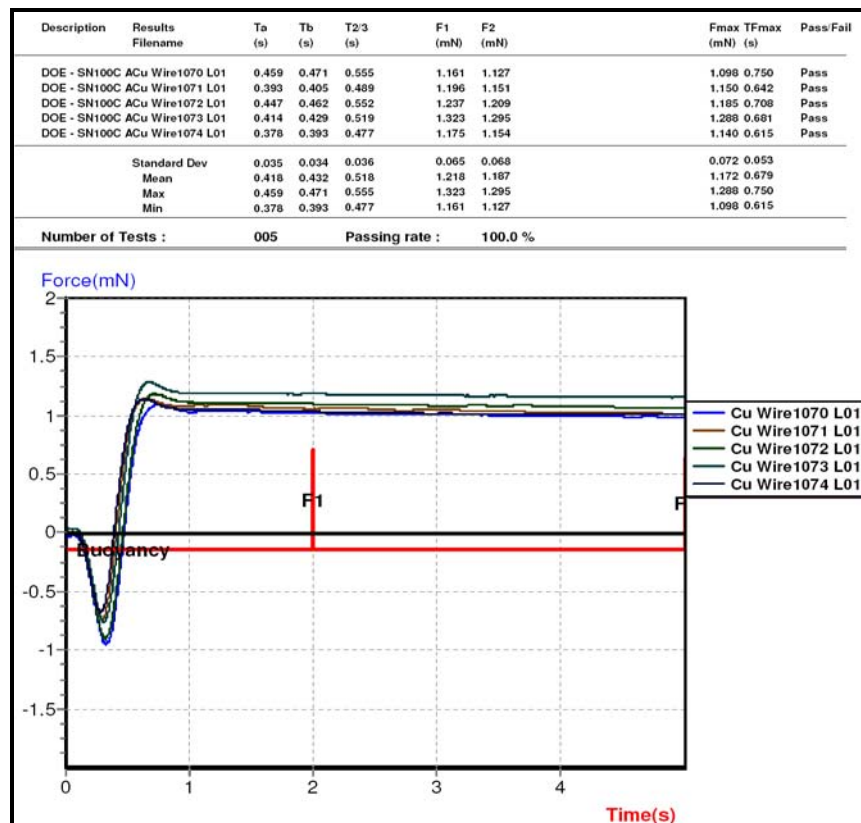
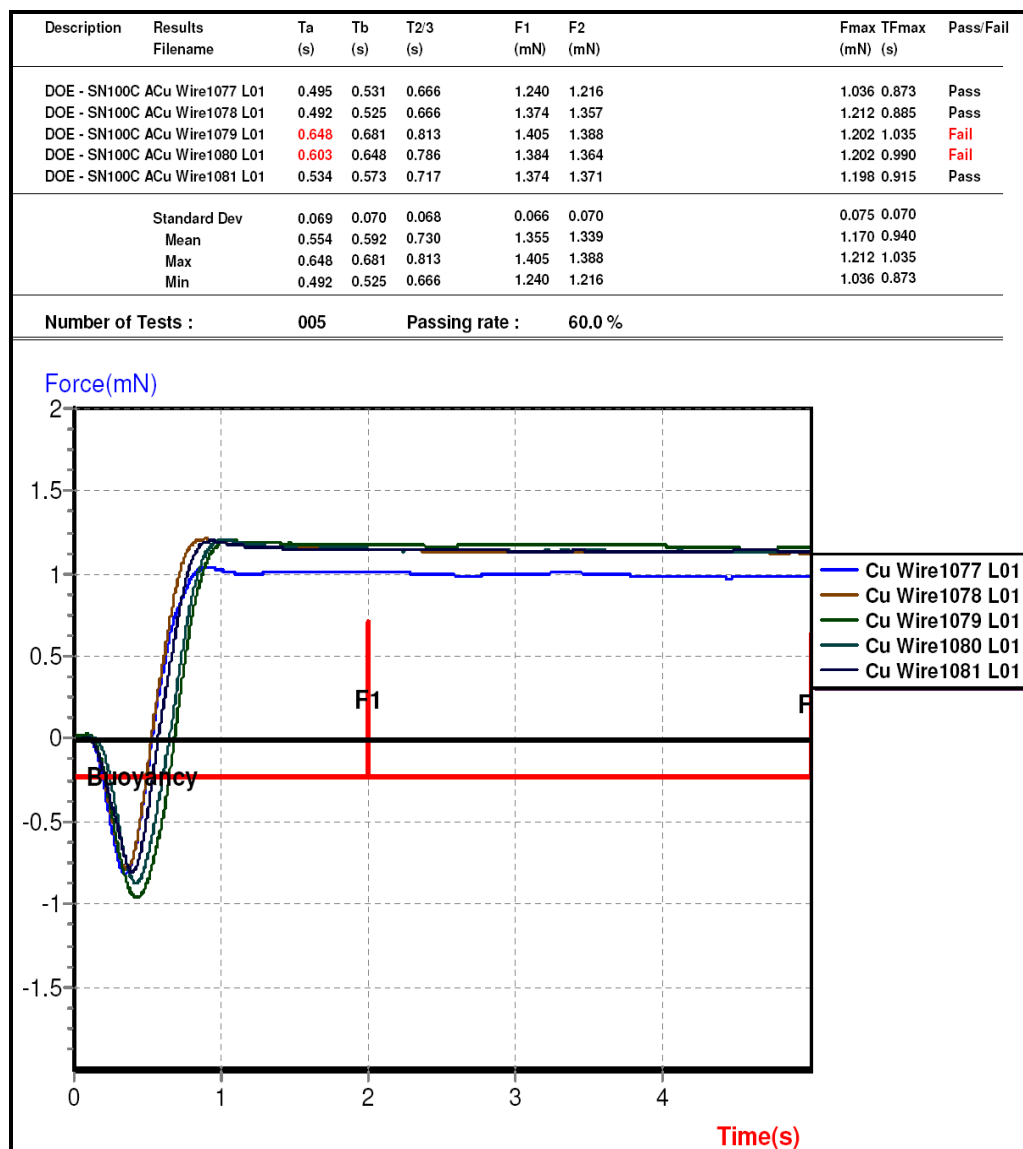


Figure 7.1 Wetting Balance Graph Ta, Tb and TFmax – least stringent optimum settings

Figure 7.2 shows the Wetting Balance graph for the optimum most stringent settings for the responses Ta, Tb, and TFmax. These settings were as follows:

**Table 7.5 Optimum Most Stringent settings for Ta, Tb and TFmax**

Responses	Factors		
	Solder Temperature	Immersion Speed	Immersion Depth
	(°C)	(mm/sec)	(mm)
<b>Ta / Tb (seconds)</b>	250	10	5
<b>TFmax (mN)</b>	250	10*	5*



**Figure 7.2 Wetting Balance Graph Ta, Tb and TFmax – most stringent optimum settings**

It can be seen that two of the five tests fail for time to buoyancy, Ta, with the IPC specification from J.STD.002C as <0.6seconds. The average of the five readings was calculated as shown:



- Ta Actual: 0.495, 0.492, 0.648, 0.603, 0.534  
Average = 0.55 seconds  
Range = 0.156  
= 0.069
- Tb Actual: 0.531, 0.525, 0.681, 0.648, 0.573  
Average = 0.59 seconds  
Range = 0.123  
= 0.070
- TFmax Actual: 0.873, 0.885, 1.035, 0.990, 0.915  
Average = 0.9396 = 0.94 seconds  
Range = 0.15  
= 0.070

Using Equation 7.17 the slope was calculated as:

$$\frac{1.323 - (-0.75)}{0.6 - 0.33} = \frac{2.073}{0.27} = 7.67$$

This value indicates an insignificant wetting characteristic than that calculated for the least stringent settings. This result is based on the optimum most stringent settings, which provide the worst possible soldering conditions from the Wetting Balance machine to discourage wetting of the solder to the test specimen.

### 7.3.2 Predicted vs. Actual Comparison for Ta, Tb, and TFmax

For Ta, Tb, and TFmax, Minitab developed three model equations based on the DoE conducted in Chapter 6. By determining the optimum least stringent and optimum most stringent settings from the Main Effects and Interaction Plots in Chapter 6, there was now an understanding of the effect of running the Wetting Balance machines main variables, solder temperature, immersion speed and immersion depth, at the lower and higher end of the tolerance. Using the three model equations:

$$1. Ta_{\text{predicted}} = C - 0.00753 T_s + 0.00222 I_s + 0.0148 I_D \quad \text{..Eq-7.00}$$

Where C is a constant 2.35

$$2. Tb_{\text{predicted}} = C - 0.00788 T_s + 0.00111 I_s + 0.0284 I_D \quad \text{..Eq-7.01}$$

Where C is a constant 2.44

$$3. TF_{\text{max predicted}} = C - 0.00427 I_s + 0.0312 I_D \quad \text{..Eq-7.03}$$

Where C is a constant 1.05

The least and most stringent optimum settings were inputted to these equations and the results gave the predicted values. The actual values were obtained by conducting experiments on the Wetting Balance machine using the least and most optimum settings. Table 7.6 shows the comparison between ‘actual’ and ‘predicted’.

**Table 7.6 Ta, Tb and TFmax ‘Predicted’ vs. ‘Actual’**

<b>Response</b>	<b>Predicted Least Stringent</b>	<b>Actual Least Stringent</b>	<b>% Difference</b>	<b>Predicted Most Stringent</b>	<b>Actual Most Stringent</b>	<b>% Difference</b>
Ta (seconds)	0.47	0.42	10%	0.56	0.55	2%
Tb (seconds)	0.49	0.43	12%	0.62	0.59	5%
TFmax (seconds)	1.08	0.68	37%	1.16	0.94	19%

For the time responses, Ta and Tb, the requirement is to reach the specification as early as possible, which indicates good wettability. For example, the predicted least stringent result is 0.47 seconds but the actual value got by running the test on the Wetting Balance machine was 0.42 seconds. However, for TFmax, which is the time to reach maximum force, the higher the maximum force the longer the TFmax so the longer the time the better in terms of good solderability. Comparing the predicted least stringent with the actual least stringent, there is a 37% difference and will be investigated in more detail in Chapter 8.

### 7.3.3 Regression Equation Verification for Fmax

Figure 7.3 shows the Wetting Balance graph for the least stringent optimum settings for the response Fmax. The significant settings are shown in Table 7.7. Again the asterisk signifies that the factor is not significant for the Fmax response but it is required to run the test and is therefore included.

**Table 7.7 Least Stringent Optimum Settings for Fmax**

<b>Responses</b>	<b>Factors</b>		
	<b>Solder Temperature (°C)</b>	<b>Immersion Speed (mm/sec)</b>	<b>Immersion Depth (mm)</b>
<b>Fmax (mN)</b>	260*	5	5

By inputting these settings into the Wetting Balance machine the graph in Figure 7.3 was generated and the average of the three Fmax results was calculated. This value, 1.18mN, is the ‘actual’ result achieved. The most stringent optimum settings for Fmax were:

1.136, 1.181, 1.212

- Fmax: Average = 1.176mN = 1.18mN  
Range = 0.076  
= 0.038

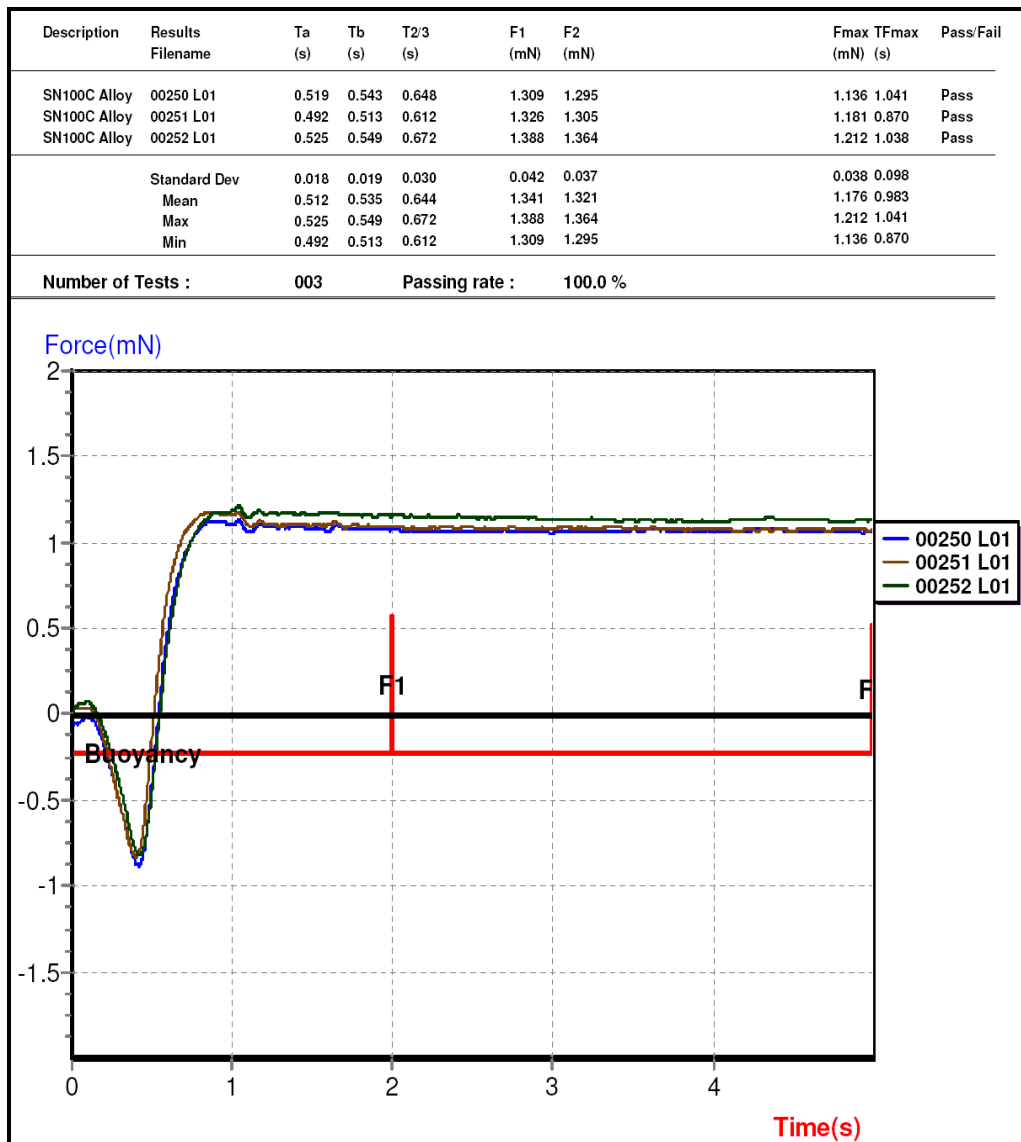


Figure 7.3 Wetting Balance Graph Fmax – least stringent optimum settings

The slope (m) was calculated using Equation 7.17 the slope was calculated as:

$$\frac{1.25 - (-0.9)}{1.0 - 0.5} = \frac{2.15}{0.5} = 10.75$$

Table 7.8 Most Stringent Optimum Settings for Fmax

Responses	Factors		
	Solder Temperature (°C)	Immersion Speed (mm/sec)	Immersion Depth (mm)
Fmax (mN)	250*	5	3

Again the average of the three Fmax results was calculated.

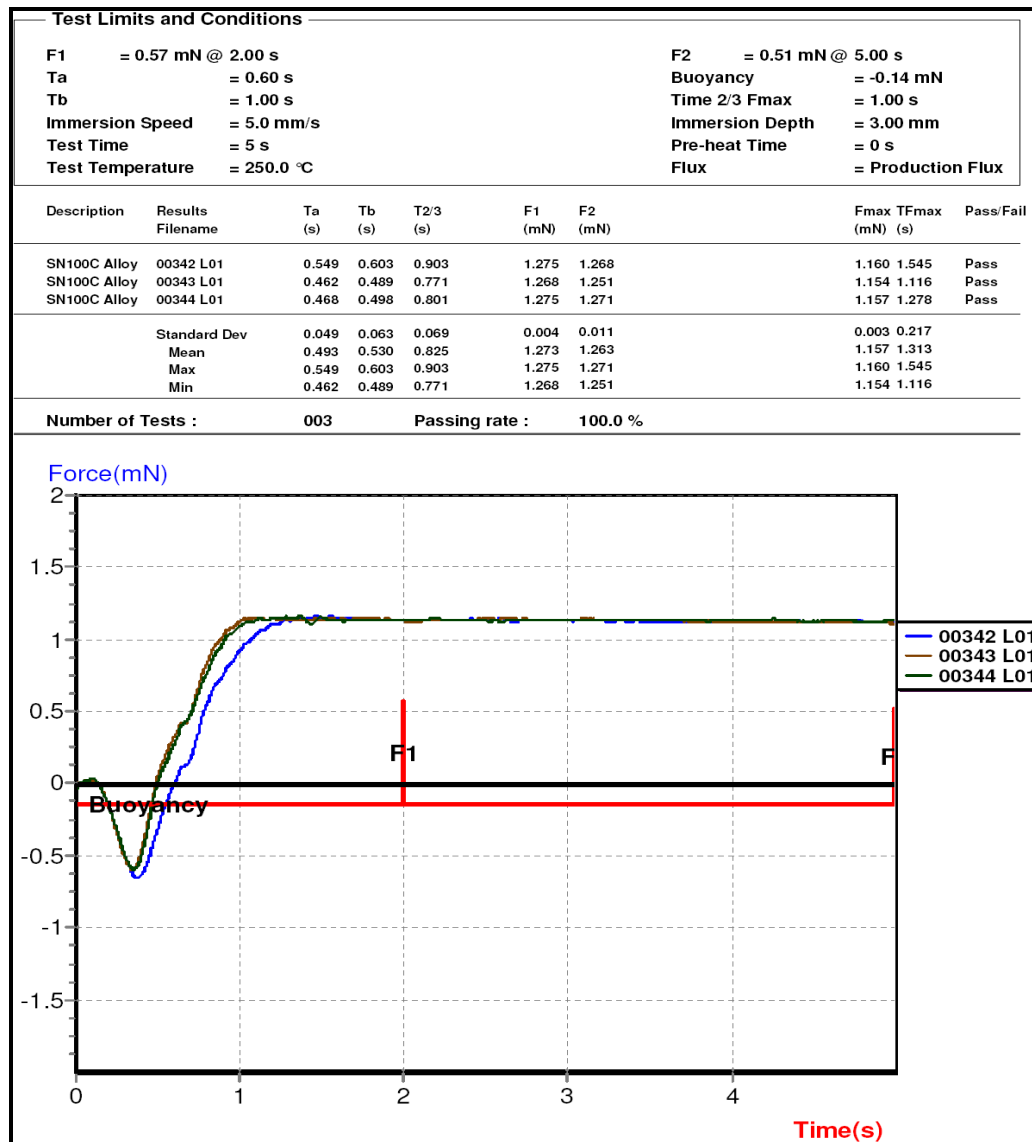
1.160, 1.154, 1.157

- Fmax:

Average = 1.157mN = 1.16mN

Range = 0.006

= 0.003



**Figure 7.4 Wetting Balance Graph Fmax – most stringent optimum settings**

Using Equation 7.17 the slope was calculated as:

$$\frac{1.1 - (-0.5)}{1.2 - 0.5} = \frac{1.6}{0.7} = 2.28$$

The slope is much greater when using the least stringent settings (10.75) when compared to the most stringent settings (2.28) for Fmax. Using the most stringent settings ensures the test specimen has the worst possible Wetting Balance settings for soldering and therefore slows the rate of wetting.

### 7.3.4 Predicted vs. Actual Comparison for Fmax

To indicate good wetting it is expected to have a high Fmax value. The test specimen is held by a linear variable differential transducer (LVDT) so the more solder that will attract to the surface the better the solderability. Therefore the greater pull on the LVDT and also the greater force. Table 7.9 shows the values for Fmax by using the model generated by Minitab:

$$\bullet \quad F_{\max} = C + 0.00142 I_s - 0.0413 I_D \quad \dots \text{Eq-7.02}$$

Where C is a constant 1.21

**Table 7.9 Fmax ‘Predicted’ vs. ‘Actual’**

Response (mN)	Predicted	Actual	%	Predicted	Actual	%
	Least	Least	Difference	Most	Most	Difference
	Stringent	Stringent		Stringent	Stringent	
Fmax	1.09	1.18	8%	1.01	1.16	15%

There is a significant difference between the actual and predicted values, 8% and 15%, respectively. However, it must be pointed out that actual Wetting Balance test results of 1.18mN and 1.16mN indicate the severity of the optimum test conditions for the least and most stringent settings. The target values are 1.09mN and 1.01mN for least stringent and most stringent settings provide robust criteria for screening poor soldering ability components.

### 7.3.5 Regression Equation Verification for F1 and F2

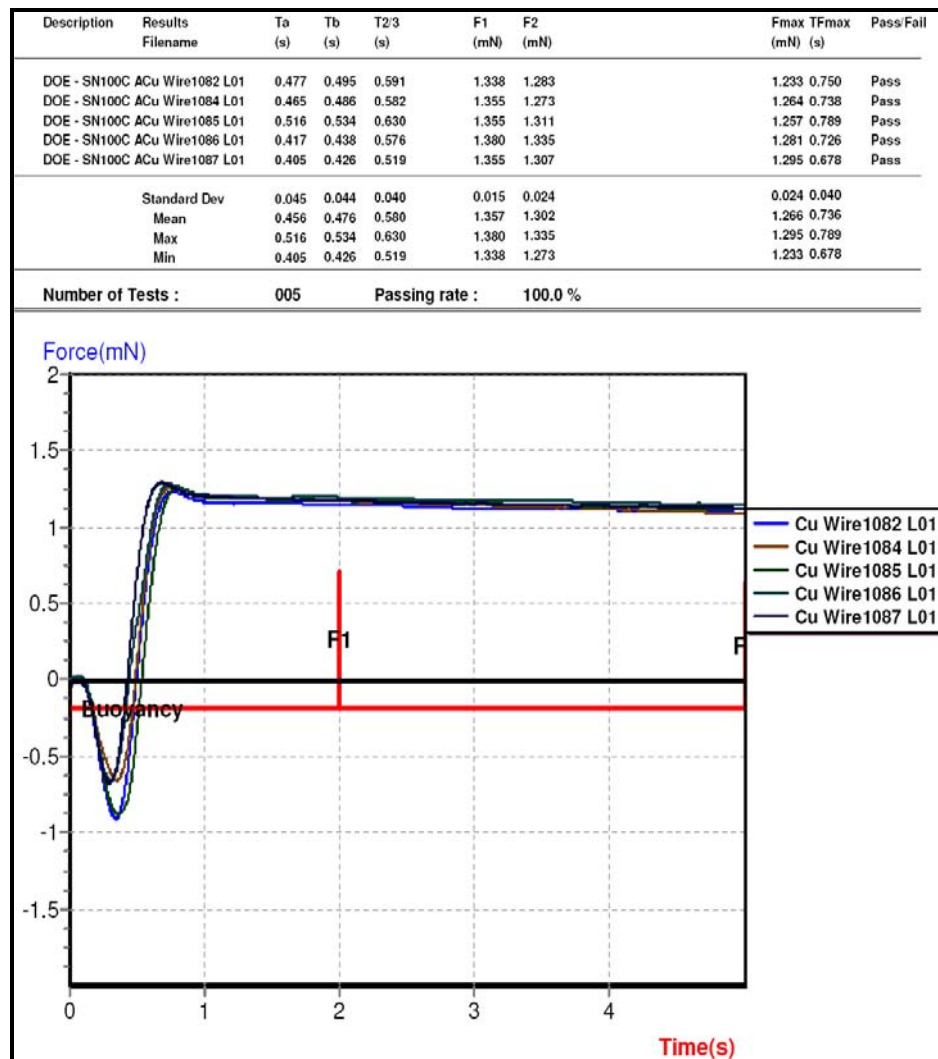
Both F1 and F2 were analysed using the optimum least stringent settings from Table 7.1. These settings are shown in Table 7.10 and the respective Wetting Balance graph is evident in Figure 7.5. As F1 and F2 occur beyond the points 2, 3, and 4 on the Wetting Balance graph (see Figure 2.22) the slope of the line would have no impact on the results and was therefore omitted.

**Table 7.10 Least Stringent Optimum Settings for F1 and F2**

Responses	Factors		
	Solder Temperature	Immersion Speed	Immersion Depth
	(°C)	(mm/sec)	(mm)
<b>F1 (mN)</b>	260*	15	4
<b>F2 (mN)</b>	260*	15*	4

As is evident from the Wetting Balance graph in Figure 7.5 the results achieved from the Wetting Balance machine using these were:

- F1: 1.338, 1.355, 1.355, 1.380, 1.355  
Average = 1.36mN  
Range = 0.042  
= 0.015
- F2: 1.283, 1.273, 1.311, 1.335, 1.307  
Average = 1.30mN  
Range = 0.062  
= 0.024



**Figure 7.5 Wetting Balance Graph for F1 and F2 – least stringent optimum settings**

Figure 7.6 shows the Wetting Balance graph using the most stringent settings, Table 7.11, for the responses F1 and F2. Again similar to all the previous responses, the average of the results for F1 and F2 was calculated. These two values for F1 (1.33mN) and F2 (1.29mN) represented the ‘actual’ value.

**Table 7.11 Most Stringent Optimum Settings for F1 and F2**

Responses	Factors		
	Solder Temperature	Immersion Speed	Immersion Depth
	(°C)	(mm/sec)	(mm)
F1 (mN)	250*	5	3
F2 (mN)	250*	5*	3

1.313, 1.351, 1.330, 1.344, 1.316

Average = 1.33mN

- F1:

Range = 0.038

= 0.017

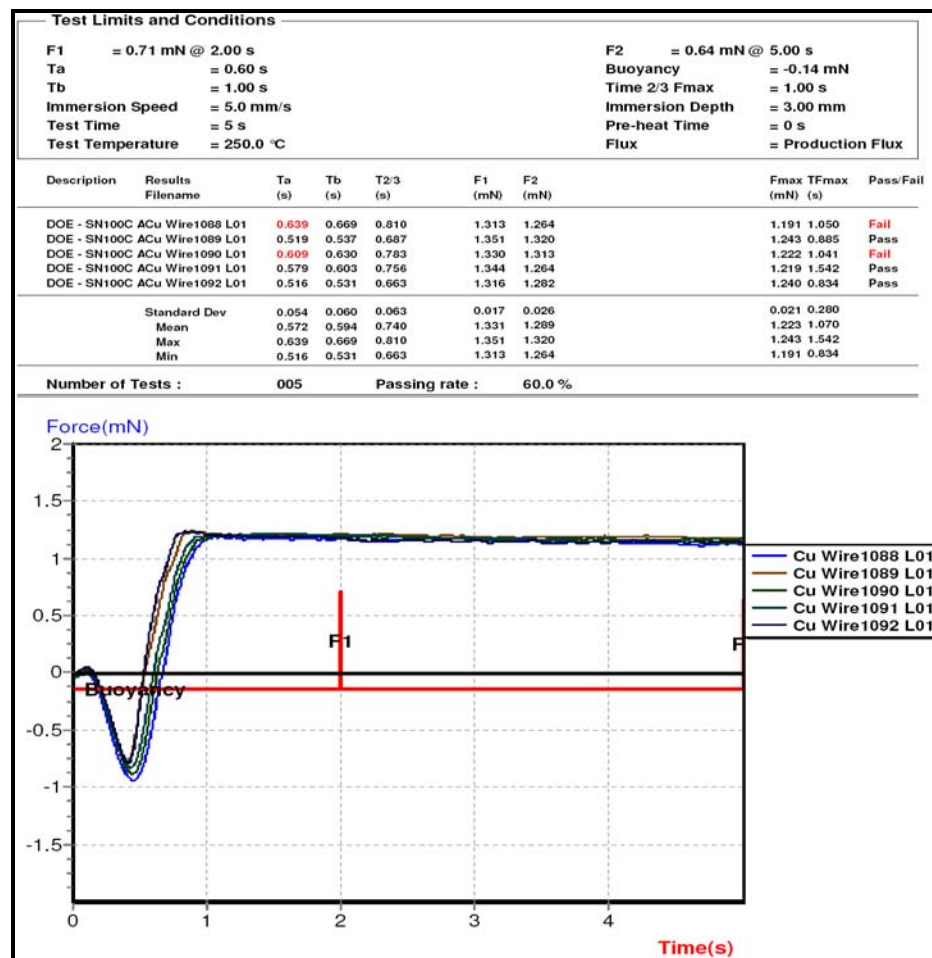
1.264, 1.320, 1.313, 1.264, 1.282

Average = 1.29mN

- F2:

Range = 0.056

= 0.027

**Figure 7.6 Wetting Balance Graph F1 and F2 – most stringent optimum settings**

### 7.3.6 Predicted vs. Actual Comparison for F1 and F2

Table 7.12 is a summary of the predicted values and the actual values for each of the responses.

**Table 7.12 Least Stringent Optimum Settings for F1 and F2**

	Predicted	Actual	%	Predicted	Actual	%
Response	Least	Least	Difference	Most	Most	Difference
	Stringent	Stringent		Stringent	Stringent	
F1 (mN)	1.33	1.36	2%	1.31	1.29	2%
F2 (mN)	1.33	1.30	2%	1.30	1.28	2%

The difference between the actual and predicted results is very small (2%) for both responses. To indicate a stable wetting it is required to have the F1 and F2 vales almost the same. If there is a big difference between F1 and F2 then it can be concluded that between two and five settings of the Wetting Balance test there is significant dewetting. The J-STD-002C specifies ‘no less than 50% of Fmax’ for F1 and ‘no less than 90% of F1’ for F2. Both these specifications are by far too lenient and can be easily achieved even by components with poor solderability.

## 7.4 Conclusions

Chapter 6 had described the theoretical analysis necessary to develop a model for each of the responses Ta, Tb, Fmax, TFmax, F1 and F2 and examined the effect a change on the significant factors, solder temperature, immersion speed and immersion depth, would have on that model value. Five Regression equations were developed in this chapter by Minitab for the each of the aforementioned responses:

$$1. Ta_{\text{predicted}} = C - 0.00753 T_s + 0.00222 I_s + 0.0148 I_D \quad \text{.....Eq-7.00}$$

Where C is a constant 2.35

$$2. Tb_{\text{predicted}} = C - 0.00788 T_s + 0.00111 I_s + 0.0284 I_D \quad \text{.....Eq-7.01}$$

Where C is a constant 2.44

$$3. F_{\text{max}} = C + 0.00142 I_s - 0.0413 I_D \quad \text{.....Eq-7.02}$$

Where C is a constant 1.21

$$4. TF_{\text{max}}_{\text{predicted}} = C - 0.00427 I_s + 0.0312 I_D \quad \text{.....Eq-7.03}$$

Where C is a constant 1.05



$$5. F1_{\text{predicted}} = C + 0.00257I_s + 0.0315I_D \quad \dots \text{Eq-7.04}$$

Where C is a constant 1.20

These equations were each verified using the optimum Wetting Balance machine parameter settings from Tables 7.1 and 7.2 and the conducting testing. As part of the detailed analysis of the equations and resulting Wetting Balance graphs, the slopes were also calculated for Ta, Tb and Fmax by using Equation 7.17 for calculating the slope (m) of a line:

$$\frac{Y2 - Y1}{X2 - X1} \quad \dots \text{Eq.-7.17 [86]}$$

These three responses occur within the points 2, 3 and 4 in Figure 2.22. F1 and F2 occur outside the slope on the Wetting Balance graph and were therefore omitted for slope calculations. Using the least stringent settings for Ta, Tb and Fmax, the co-ordinates from the resulting Wetting Balance graph were obtained using a software, MUST II +. With these co-ordinates the slope was calculated using Equation 7.17. It was evident that the line slopes were greater for the least stringent settings than those obtained for the most stringent settings due to the effect each had on the soldering.

It is evident at this stage of the project that the prediction equations are accurate indicators to have before commencing any testing. Table 7.13 is an overview of the actual vs. predicted values.

**Table 7.13 Overview of Predicted vs. Actual Response Values**

	Predicted	Actual	%	Predicted	Actual	%
Response	Least	Least	Difference	Most	Most	Difference
	Stringent	Stringent		Stringent	Stringent	
Ta	0.47	0.42	10%	0.56	0.55	2%
(seconds)						
Tb	0.49	0.43	12%	0.62	0.59	5%
(seconds)						
Fmax	1.09	1.18	8%	1.01	1.16	15%
(mN)						
TFmax	1.08	0.68	37%	1.16	0.94	19%
(seconds)						
F1 (mN)	1.33	1.36	2%	1.31	1.29	2%
F2 (mN)	1.33	1.30	2%	1.30	1.28	2%

The percentage difference between the Predicted vs. Actual for the least and most stringent settings is not significant except for the Fmax and TFmax results. The TFmax results indicate the time to reach the maximum forces, Fmax. It is evident that the differences are significant, 37% and 19%, and for Fmax when using the most stringent setting a 15% difference is evident. This will be evaluated in more detail in Chapter 8.

To further validate the accuracy of these models, Chapter 8 will assess the relationship between the factors (solder temperature, immersion speed and immersion depth) and each of the responses (Ta, Tb, TFmax, Fmax, F1 and F2). As mentioned earlier, the test specimen used for the Wetting Balance test analysis in this project were 20mm lengths of 0.9mm diameter copper wires. The reasoning for this was to try and eliminate as much as possible any effects of poor soldering ability that could be evident on component leads and affect the results. Now that the investigations to date have been successful in developing accurate Regression equations, a sample of different components will be tested using the Wetting Balance machine and the results compared to the model equations in Chapter 8.

## Chapter 8 Statistical Analysis Model

### 8.1 Introduction

In Chapter 7, six mathematical equations (Eqn. 7.00, 7.01, 7.02, 7.03, 7.04, 7.05) describing the six responses (Ta, Tb, Fmax, TFmax, F1, F2) were derived. In order to establish a relationship between the factors (solder temperature, immersion speed and immersion depth) and each of the aforementioned responses, plots will be generated between the significant factors (Figure 8.1 to 8.5) and linear relationships developed using the most stringent and least stringent settings developed in Chapter 6. These are listed in Tables 8.1 and 8.2.

**Table 8.1 Least Stringent Settings**

Responses	Factors		
	Solder Temperature	Immersion Speed	Immersion Depth
	(°C)	(mm/sec)	(mm)
<b>Ta / Tb</b>	260	15	3
<b>TFmax / Fmax</b>	260	5	5
<b>F1 / F2</b>	260	15	4

**Table 8.2 Most Stringent Settings**

Responses	Factors		
	Solder Temperature	Immersion Speed	Immersion Depth
	(°C)	(mm/sec)	(mm)
<b>Ta / Tb</b>	250	10	5
<b>TFmax / Fmax / F1 / F2</b>	250	5	3

The linear relationships between the factors provide an indication of the accuracy for the predicted values against the actual values. The linear relationships are calculated by determining the equation of each line in Figures 8.1 to 8.5 using Equation 8.1,

$$\bullet \quad y = mx + C \quad \text{.....Eq-8.1}$$

The strength of the relationship is assessed by an  $R^2$  value that provides a measure of how well future outcomes are likely to be predicted by the mathematical models. The requirement is to have  $R^2$  equal or as close as possible to one. [87] An  $R^2$  of one indicates a line is linear and fits the three points accurately. One is the target value for each  $R^2$ . The

plots in Figures 8.1 to 8.5 were generated using the same results from the DoE in Chapter 6 (243 runs) using 0.9mm diameter copper wires.

Up to this stage of the project 0.9mm diameter copper wires were used for all Wetting Balance testing due to the potential solderability variation between component leads that could affect the results. To further assess the accuracy of the mathematical models the optimum settings for the least and most stringent settings will be tested using through-hole components, relay and socket connectors, with a history of solderability problems from a series production line. In addition to through-hole relay and socket connector components, a through-hole LED (light emitting diode) with no known solderability issue will be also tested. XRF (X-Ray Fluorescence) will be used to verify the metal plating thickness of the component leads to determine if there was any variation that could potentially affect the solderability results. The focus of this chapter is to finalise the optimum settings to be used when assessing the solderability of components. These optimum settings will be within the specification limits of the various international standards, which currently have conflicting information's between each.

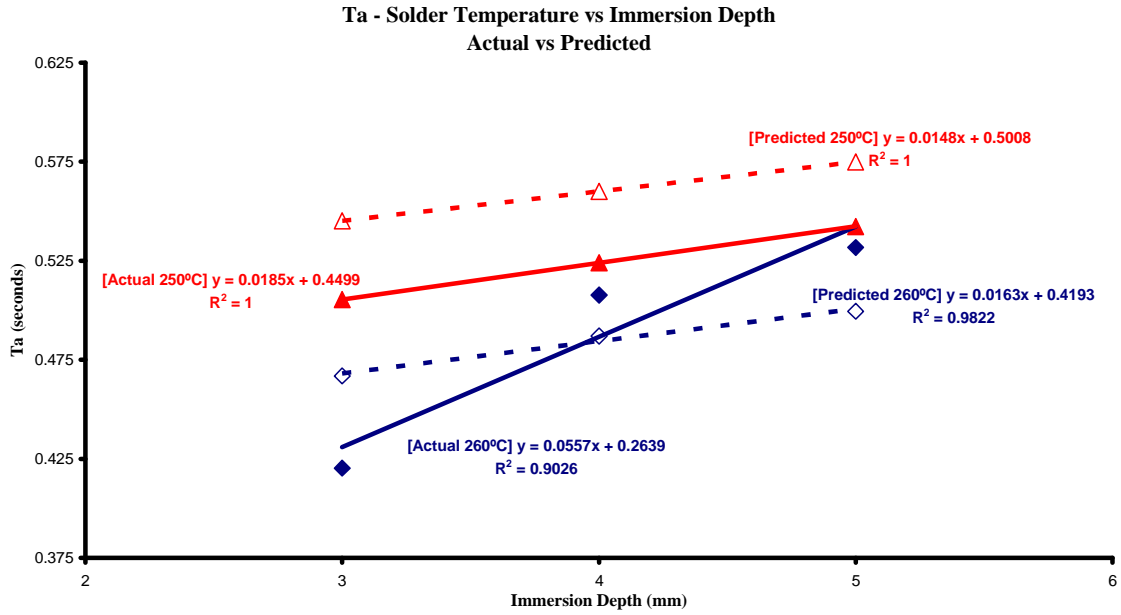
## **8.2 Linear Relationship Verification**

The linear relationship for the responses  $T_a$ ,  $T_b$ ,  $F_{max}$ ,  $TF_{max}$ ,  $F_1$ , and  $F_2$  with each of the significant factors, Solder Temperature, Immersion Speed and Immersion Depth are discussed in this section. It should be noted at this point that each linear relationship is based on nine readings. To calculate each point on the graphs in Figures 8.1, 8.2, 8.3, 8.4 and 8.6, an average of three readings is calculated. These readings are actual Wetting Balance test values. The linear relationship graphical representations in Figures 8.1, 8.2, 8.3, 8.4 and 8.6 provide a reasonably good indication of the correlation for each response and the affecting machine parameters.

### **8.2.1 Statistical Analysis Model, $T_a$**

Figure 8.1 shows the linear relationship between solder temperature and immersion depth and the effect of both on the time to reach buoyancy,  $T_a$ , using the least and most stringent settings from Tables 8.1 and 8.2.

In Figure 8.2 the red lines represent a solder temperature of 250°C (most stringent) and the blue lines represent a solder temperature of 260°C (least stringent). The broken lines for both solder temperatures represent the predicted values (model equations 7.00 to 7.05) and the solid lines represent the actual values (achieved by testing with 0.9mm diameter copper wires). For each point of the graph the average of three results is calculated.



**Figure 8.1 Plot of Ta - Solder Temperature against Immersion Depth**

It is apparent that a good linear relationship between solders temperature and immersion depth exist for Ta due to the high  $R^2$  values evident in Figure 8.1. This conclusion is based on the range of results experimented in this thesis. These relationships obey the equations:

- Most Stringent Actual (250°C);  $y = 0.0185x + 0.04499$ ... Eq-8.2
- Most Stringent Predicted (250°C);  $y = 0.0148x + 0.5008$  ... Eq-8.3
- Least Stringent Actual (260°C);  $y = 0.0557x + 0.2639$  ... Eq-8.4
- Least Stringent Predicted (260°C);  $y = 0.0163x + 0.4193$ ... Eq-8.5

Where;  $y = Ta$

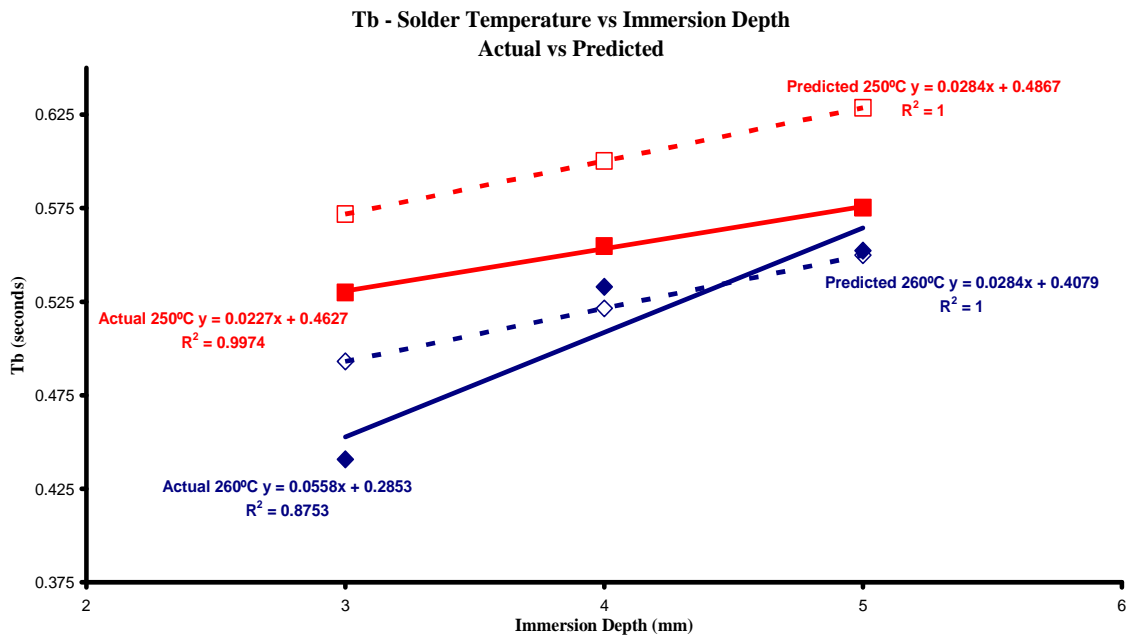
$x =$  immersion depth

### 8.2.2 Statistical Analysis Model, Tb

The statistical analysis for the time to reach the zero line, Tb, was generated using the same method that was used for Ta in the previous section and is represented in Figure 8.2. Again similar to Ta, the relationship is linear between solder temperature and immersion depth and this is evident with Equations 8.6, 8.7, 8.8 and 8.9. The blue solid and broken lines represent the data for least stringent actual and predicted respectively. The red solid (actual) and broken (predicted) lines represent for the most stringent values.

- Most Stringent Actual (250°C);  $y = 0.0227x + 0.4627$  ..... Eq-8.6
- Most Stringent Predicted (250°C);  $y = 0.0284x + 0.486$  ..... Eq-8.7
- Least Stringent Actual (260°C);  $y = 0.0558x + 0.2853$  ..... Eq-8.8
- Predicted (260°C);  $y = 0.0284x + 0.4079$  ..... Eq-8.9

Where;  $y = Tb$  and  $x =$  immersion depth



**Figure 8.2 Plot of Tb - Solder Temperature against Immersion Depth**

Again high  $R^2$  values in Figure 8.2 indicate a reasonable linear relationship between the model Equation 7.01 and the actual Wetting Balance test results based on the range of results experimented in this thesis.

### 8.2.3 Statistical Analysis Model, Fmax

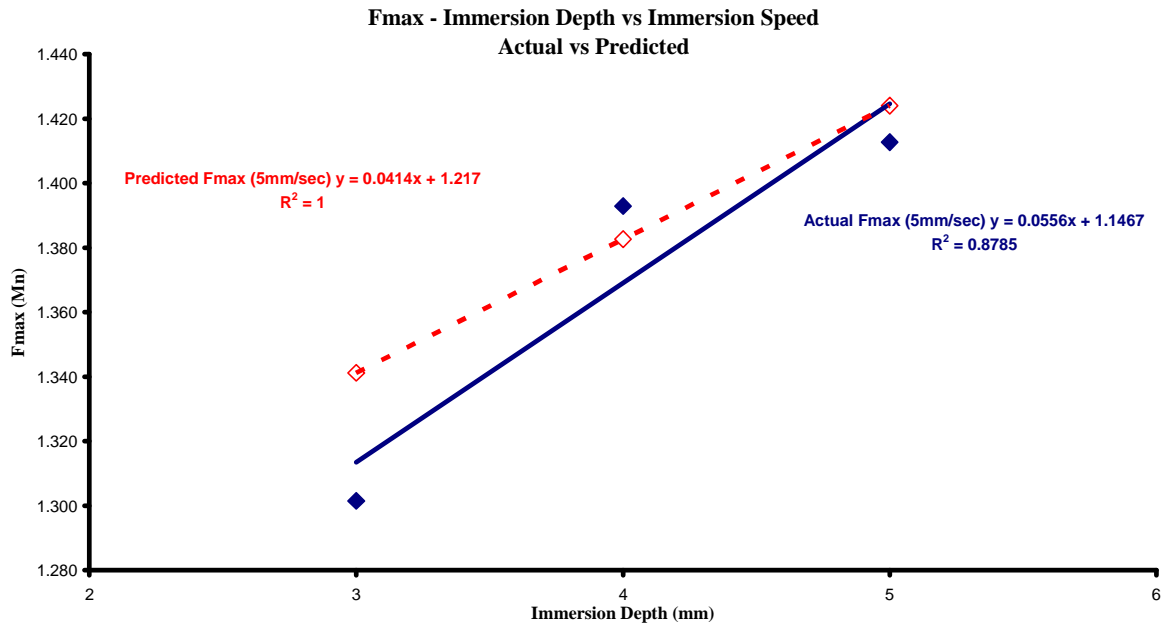
The factors that have a significant effect on the maximum force reached during the Wetting Balance test are immersion speed and immersion depth. Figure 8.3 shows the linear relationship for both factors and the effect on the Fmax result. The immersion speed of 5mm/sec is optimum for the least stringent and the most stringent settings. The linear relationships are represented by the equations:

- Actual (5mm/sec);  $y = 0.0556x + 1.1467$  ..... Eq-8.10

- Predicted (5mm/sec);  $y = 0.0414x + 1.217$  ..... Eq-8.11

Where:  $y = F_{max}$   
 $x = \text{Immersion depth}$

The blue trend line is the plot of the data obtained from the Wetting Balance machine and the red line is obtained from the model Equation 7.02 using the optimum settings from Table 8.1. The data for predicting Fmax can be successfully aligned into Equations 8.10 and 8.11.



**Figure 8.3 Plot of Fmax – Immersion depth against Immersion Speed**

Using the formula from the standard J-STD-002C:

$$F_{\max} = [0.5P - 0.07V] \quad \dots \text{Eq-8.12}$$

Where;

0.5P is the maximum force

0.5 is the surface tension ( $\gamma$ ) of SN100C solder

P is the circumference of the wire

0.07V is the buoyancy force

0.07 is the density ( $\rho$ ) of the SN100C solder

V is the immersed volume

Immersion depth of 4mm used

$$P = 2 \pi r$$

$$\Rightarrow P = 2 \times \pi \times 0.45$$

$$\Rightarrow P = 2.8274 \text{ mm}$$

$$0.5P = 0.5 \times 2.8274$$

$$\Rightarrow 0.5P = 1.4137 \text{ mm}$$

... Eq-8.13

$$\begin{aligned} V &= \left( \frac{d^2}{4} \right) \times 4 \\ \Rightarrow V &= \left( \frac{(0.9)^2}{4} \right) \times 4 \\ \Rightarrow V &= (0.9)^2 \\ \Rightarrow V &= 2.5446 \text{ mm}^3 \quad \dots \text{Eq-8.14} \end{aligned}$$

$$\begin{aligned} \therefore 0.07V &= 0.07 \times 2.5446 \\ \Rightarrow 0.07V &= 0.17818 \end{aligned}$$

$$\begin{aligned} \therefore F_{\text{max}} &= 1.4137 - 0.17818 \\ \Rightarrow F &= 1.2355 \text{ mN} \Rightarrow 1.24 \text{ mN} \end{aligned}$$

The Fmax value calculated using Equation 8.12 as per J-STD-002C is 1.24mN. Using the predicted model equation developed from Figure 7.11;

$$\begin{aligned} \blacksquare y &= 0.0414x + 1.217 \quad \dots \text{Eq-8.15} \\ \blacksquare F_{\text{max}} &= 0.0414(4) + 1.217 \\ \blacksquare F_{\text{max}} &= 1.3826 = 1.38 \text{ mN} \end{aligned}$$

The difference between the Fmax values in Equations 8.14 and 8.15 is 0.14mN, a 10% difference. Further analysis of this difference will be assessed in this chapter using components.

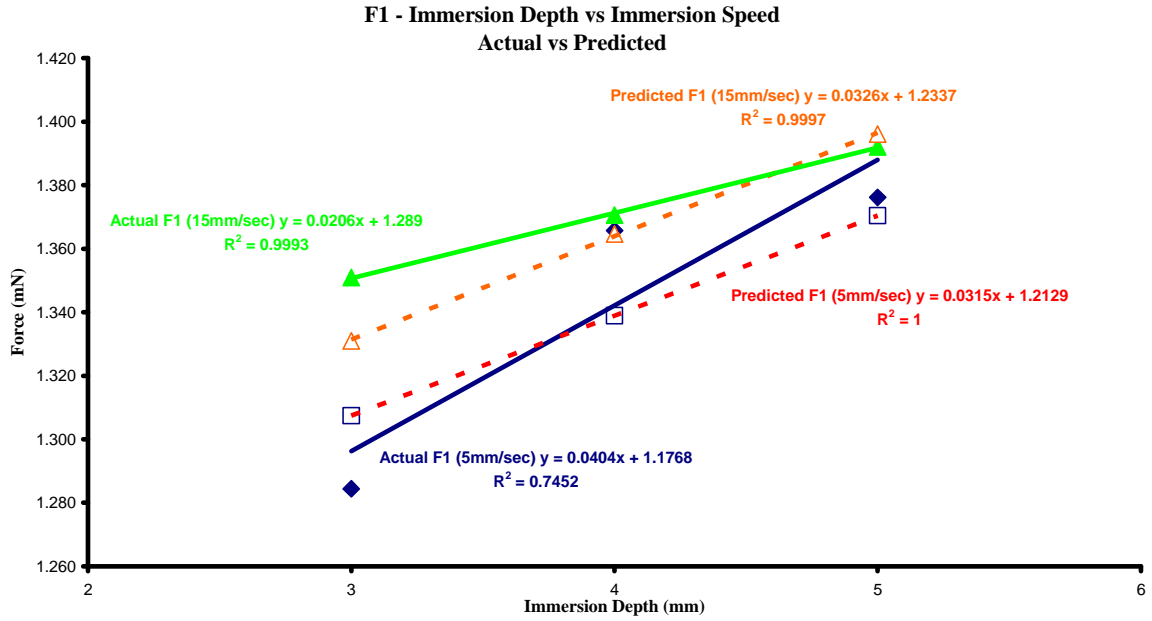
#### 8.2.4 Statistical Analysis Model, F1

From the analysis to generate Figure 8.4 there were some outliers, caused by dried flux on the test specimen, that were removed as these were affecting actual linear relationship for an immersion speed of 15mm/sec. Other forms of regression analysis such as log and power were investigated but the outliers were very evident and it was decided to remove them to avoid any inaccuracy. When these outliers were included the  $R^2$  was at 0.2147 and after removing them the  $R^2$  increased to 0.9993. From 8.4 there are four linear relationships evident and are represented by the Equations 8.16, 8.17, 8.18 and 8.19. Immersion speeds of 5mm/sec and 15mm/sec are the optimum for the most and least stringent settings respectively.

- Most Stringent Actual F1 (5mm/sec);  $y = 0.0404x + 1.176 \quad \dots \text{Eq-8.16}$
- Most Stringent Predicted F1 (5mm/sec);  $y = 0.0315x + 1.2129 \quad \dots \text{Eq-8.17}$
- Most Stringent Actual F1 (15mm/sec);  $y = 0.0206x + 1.289 \quad \dots \text{Eq-8.18}$
- Most Stringent Predicted F1 (15mm/sec);  $y = 0.0326x + 1.2337 \quad \dots \text{Eq-8.19}$



Where:  $y = F1$  and  $x = \text{Immersion depth}$



**Figure 8.4 Plot of F1 – Immersion Depth against Immersion Speed**

The Equation given in J-STD-002C to determine the F1 value is:

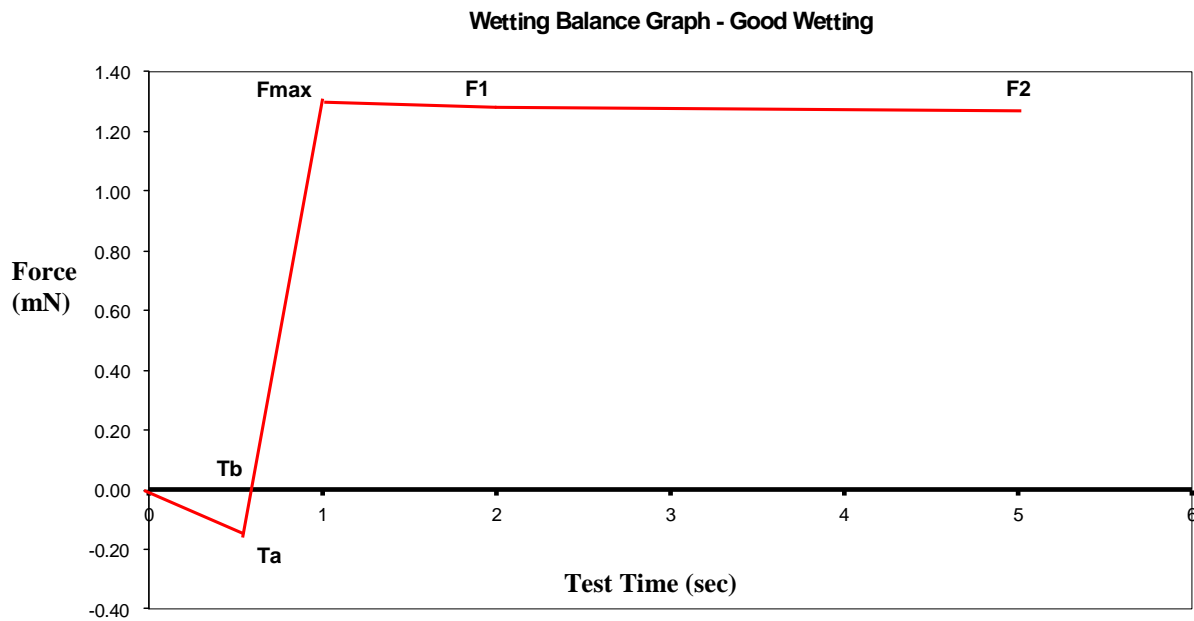
$$F1 = \left( \frac{F_{\max}}{2} \right) \Rightarrow F1 = \left( \frac{1.42}{2} \right) = 0.71\text{mN} \quad \dots \text{Eq-8.20}$$

And comparing this to the equation generated from Figure 7.12 at 3mm immersion depth;

$$\begin{aligned} Y &= 0.0404x + 1.1768 \\ F1 &= 0.0404(3) + 1.1768 \\ F1 &= 1.298\text{mN} = 1.30\text{mN} \end{aligned} \quad \dots \text{Eq-8.21}$$

It is evident from this comparison that Equation 8.20 given in J-STD-002C to calculate a value of 0.71mN is not reflective of the actual value 1.30mN. It was highlighted earlier in Section 7.3.6 that the method for calculating F1 using the international standard Equation 8.20 was not a reliable means for calculating a force reading after two seconds and should be reviewed and reconsidered. A 50%  $F_{\max}$  for the force after two seconds is a lenient specification for a component to achieve. In fact putting it into context in terms of the solderability, there is an allowance of a 50% decrease in force in less than one second,  $F_{\max}$  to F1, which is too extreme. For a good wetting curve, it is required to have a short reduction in the force after the  $F_{\max}$  value is achieved, which indicates a strong wetting characteristic. [22] Figure 8.5 is a graphical representation showing good wetting by means of a Wetting Balance curve. What is evident in this graph is a stable wetting after it reaches the maximum force,  $F_{\max}$ . After two and five seconds of testing in the Wetting Balance machine the solder maintains the force for the test duration thus indicating the solder

attracting test specimen. Going by the specification for F1 in J-STD-002C – there is an allowance of a 50% reduction in force, which is very significant in terms of component solderability. This is highlighted in Figure 8.5.



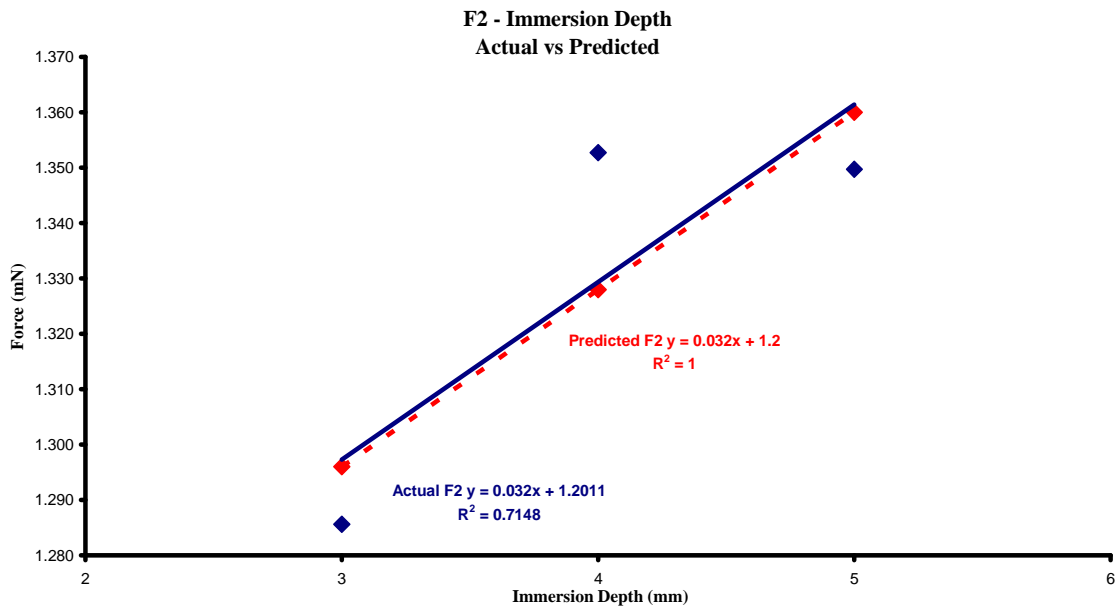
**Figure 8.5 Good Wetting – Wetting Balance Graphical example**

### 8.2.5 Statistical Analysis Model, F2

Immersion depth is the only factor that has a significant effect on the force reached at five seconds and in Figure 8.6 the relationship between both is plotted. The blue trend line contains the actual values and the predicted values are contained within the broken red line. As is evident from the graph in Figure 8.6, an immersion depth of 3mm will give a lower F2 value than an immersion depth of 5mm. The reason for this is because there is 2mm less surface area for the solder to wet to on a 3mm depth then with the 5mm depth and therefore less weight on the test specimen (0.9mm diameter copper wire) so less force recorded on the Wetting Balance machine. The model equations are:

- Actual F2 =  $y = 0.032x + 1.2011$  ..... Eq-8.22

- Predicted F2 =  $y = 0.032x + 1.2$  ..... Eq-8.23



**Figure 8.6 Plot of F2 – Immersion Depth**

Again doing a comparison with the value from the J-STD-002C that states no less than 90% of F1:

$$F2 = F1 \times 0.9 \Rightarrow F2 = 0.71 \times 0.9 = 0.64 \text{ mN} \quad \dots \text{Eq-8.24}$$

From the equation generated in Figure 8.5;

$$\text{Actual } F2 = y = 0.032x + 1.2011$$

$$F2 = 0.032(3) + 1.2011 \Rightarrow F2 = 1.2971 = 1.30 \text{ mN} \quad \dots \text{Eq-8.25}$$

Using ‘no less than 90% of F1’ for the F2 values would be a good indication to have but when the F1 values are under-achieved, the F2 values are also affected. As mentioned earlier, the J-STD-002C specification of less than 50% of Fmax for F1 will be reviewed and reconsidered in the next section using components. The model equations generated to predict the responses, Ta, Tb, Fmax, TFmax, F1 and F2, were verified as being accurate indicators to have prior to Wetting Balance testing based on the R<sup>2</sup> results. To ascertain if the soldering ability of component leads can be predicted using the model equations, a batch of different component types will be tested and the results compared to the predicted values from the model equations 7.00, 7.01, 7.01, 7.03, 7.04, and 7.05.

### 8.3 Regression Model Verification using Components

The analysis of the Wetting Balance test throughout this project was conducted using 0.9mm diameter copper wires to avoid any solderability variation that could be evident on component leads. In Chapter 3, XRF measurements of component leads found significant

variation in metal plating thickness that could affect solderability results. XRF measurements will be again used to check the plating thickness of the components used in this section of analysis.

Through-hole (TH) components such as relays, socket connectors and LED's will be assessed using the most stringent and least stringent settings on the Wetting Balance machine. The reason for not testing small SMD components such as resistors and capacitors was because these are more suited to the solder globule method in the Wetting Balance test. In some cases the immersion depths of 5mm would completely submerge the SMD component in the solder bath resulting in error readings and for this reason the solder globule is more suited to smaller components. The through-hole relay and socket connector are components with a long history of solderability issues and combined accounted for approximately 430PPM. Various investigations such as Wetting Balance testing using the current test criteria and cross-section analysis have not determined a root cause to the problem. Wetting Balance tests were 'pass' results for each of the responses using conventional test criteria. Figure 8.7 shows the Wetting Balance test results.

Test Limits and Conditions									
F1 = 0.57 mN @ 2.00 s					F2 = 0.51 mN @ 5.00 s				
Ta = 0.60 s					Buoyancy = -0.14 mN				
Tb = 1.00 s					Time 2/3 Fmax = 1.00 s				
Immersion Speed = 5.0 mm/s					Immersion Depth = 3.00 mm				
Test Time = 5 s					Pre-heat Time = 0 s				
Test Temperature = 260.0 °C					Flux = Production Flux				
Description	Results Filename	Ta (s)	Tb (s)	T2/3 (s)	F1 (mN)	F2 (mN)	Fmax (mN)	TFmax (s)	Pass/Fail
SN100C Alloy	00027 L01	0.567	0.579	0.708	1.371	1.354	1.271	0.897	Pass
SN100C Alloy	00029 L01	0.573	0.588	0.702	1.247	1.220	1.129	0.867	Pass
SN100C Alloy	00030 L01	0.555	0.570	0.714	1.289	1.264	1.174	0.897	Pass
Standard Dev		0.009	0.009	0.006	0.063	0.068	0.072	0.017	
Mean		0.565	0.579	0.708	1.302	1.279	1.191	0.887	
Max		0.573	0.588	0.714	1.371	1.354	1.271	0.897	
Min		0.555	0.570	0.702	1.247	1.220	1.129	0.867	
Number of Tests :		003		Passing rate :		100.0 %			

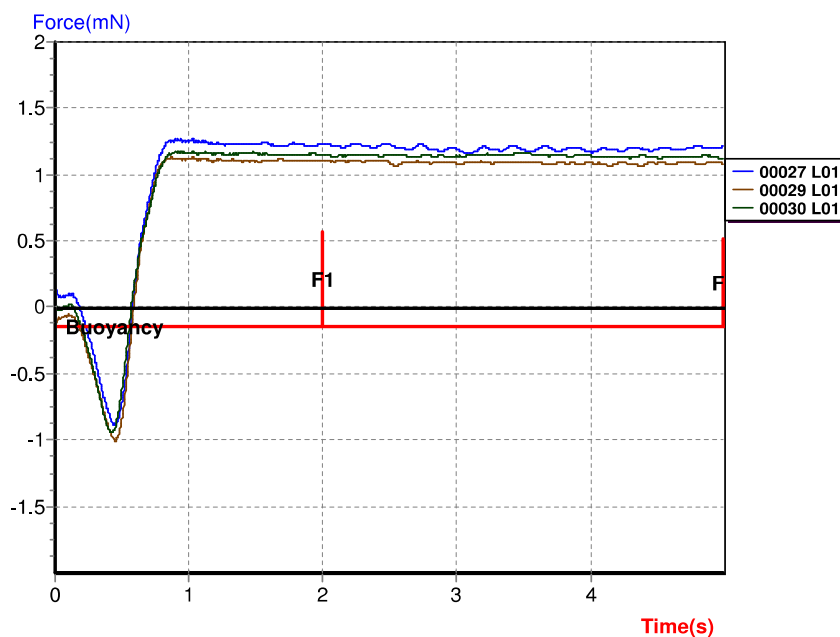
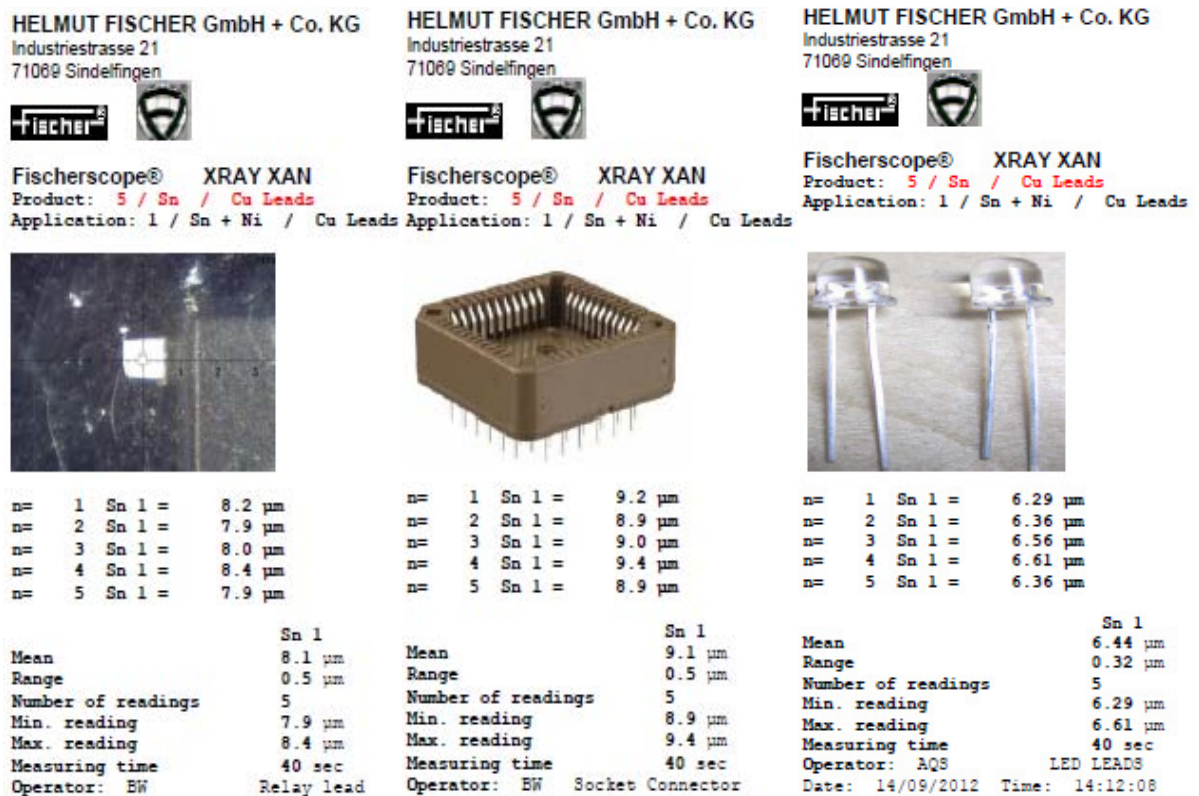


Figure 8.7 Relay Wetting Balance Test Results using Conventional Settings

The LED components were performing well within a series production line and had a performance level of less than 2PPM.

XRF measurements of the relay, socket connector and LED lead showed uniform plating thickness. Five leads on five different relay, socket connectors and LED's from the same batch were assessed. The results are shown in Figure 8.8.



**Figure 8.8 XRF Measurement of Relay leads (left), Socket Connector (centre) and LED leads (right)**

The lead diameter of the relay is 1mm, the socket connector lead diameter is 0.8mm, and the diameter of the LED is approximately 0.9mm which are approximately the size of the test specimen used so far in this project, 0.9mm diameter copper wires. For this reason all three-component types will be assessed using the most stringent and least stringent settings, all of which are within the limits of the various IPC standard setting requirements. These settings are taken from Table 8.1 and Table 8.2. It will then be determined if the model equations generated are accurate indicators to use for lead diameters of 0.9mm  $\pm$  0.1mm. For each component, five leads were tested and the average was calculated for accuracy purposes. The model equations developed in Chapter 7 will be tested using the through-hole relay, socket connector and LED components with the same alloy used throughout this project, SN100C. These model equations are:

$$Ta_{\text{predicted}} = C - 0.00753 T_S + 0.00222 I_S + 0.0148 I_D \quad \dots \text{Eq-7.00}$$

Where C is a constant 2.35

$$Tb_{\text{predicted}} = C - 0.00788 T_S + 0.00111 I_S + 0.0284 I_D \quad \dots \text{Eq-7.01}$$

Where C is a constant 2.44

$$F_{\text{max}} = C + 0.00142 I_S - 0.0413 I_D \quad \dots \text{Eq-7.02}$$

Where C is a constant 1.21

$$TF_{\text{max}_{\text{predicted}}} = C - 0.00427 I_S + 0.0312 I_D \quad \dots \text{Eq-7.03}$$

Where C is a constant 1.05

$$F1_{\text{predicted}} = C + 0.00257 I_S + 0.0315 I_D \quad \dots \text{Eq-7.04}$$

Where C is a constant 1.20

$$F2_{\text{predicted}} = C + 0.0320 I_D \quad \dots \text{Eq-7.05}$$

Where C is a constant 1.20

Where:  $T_S$  = Solder Temperature (°C)

$I_S$  = Immersion Speed (mm/sec)

$I_D$  = Immersion Depth (mm)

C = Constant

By inputting the least stringent and most stringent settings to each of the equations 7.00 to 7.05 the calculated results will be compared with the actual values determined from conducting the tests on the Wetting Balance machine using the through-hole relay, through-hole socket connectors and through hole LED components. This will indicate the reliability of the model equation across a range of similar size diameter leads to that of the 0.9mm diameter copper wires.

### 8.3.1 Regression Model Verification – Poor Solderability Components

Appendices 9.1 to 9.12 show all the Wetting Balance graphs for each of the verification tests using relays and socket connectors. Tables 8.3 and 8.4 summarise the averages of these Wetting Balance graphs into ‘Actual’ vs. ‘Calculated’ values achieved using the Wetting Balance machine and model equations respectively for through-hole relays and socket connectors. As mentioned earlier, both components tested have a long history of

solderability problems. The Wetting Balance tests carried out passed the J-STD-002C specification for Ta (<0.6 seconds) and Tb (<1 second) when using the least stringent settings and this can be seen in Tables 8.3 and 8.4. The current lenient specification limits for Ta and Tb within the various international standards do not screen out the poor solderability components.

**Table 8.3 Actual vs. Calculated – TH Relays**

TH Relays	Least Stringent Actual	Calculated
Ta (sec)	0.550	0.467
Tb (sec)	0.573	0.493
F1 (mN)	1.320	1.396
F2 (mN)	1.313	1.360
Fmax (mN)	1.084	1.424
TFmax (sec)	1.489	0.873

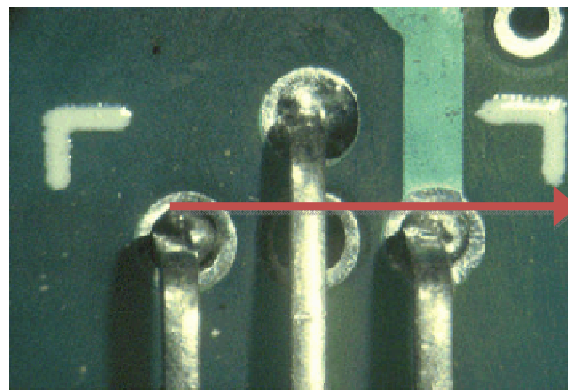
TH Relays	Most Stringent Actual	Calculated
Ta (sec)	0.884	0.564
Tb (sec)	0.949	0.623
F1 (mN)	1.225	1.315
F2 (mN)	1.286	1.296
Fmax (mN)	1.111	1.341
TFmax (sec)	2.276	0.935

**Table 8.4 Actual vs. Calculated – TH Socket Connectors**

TH Socket Connectors	Least Stringent Actual	Calculated
Ta (sec)	0.531	0.467
Tb (sec)	0.551	0.493
F1 (mN)	1.326	1.396
F2 (mN)	1.312	1.360
Fmax (mN)	1.118	1.424
TFmax (sec)	1.411	0.873

TH Socket Connectors	Most Stringent Actual	Calculated
Ta (sec)	0.8316	0.564
Tb (sec)	0.8912	0.623
F1 (mN)	1.2396	1.315
F2 (mN)	1.2494	1.296
Fmax (mN)	1.1452	1.341
TFmax (sec)	3.1602	0.935

Ta and Tb values of 0.550 seconds and 0.573 seconds in Table 8.3 for the through-hole relay would be deemed good soldering components based on the current specification criteria stated within the many international standards. This is also evident in Table 8.4 where a Ta value of 0.531 seconds and a Tb value of 0.551 seconds, all meet the specifications requirements when using the least stringent settings. However, when the most stringent settings are used both components fail which is reflective of the performance of both components when used on a series production line. Figure 8.9 is an image of the poor wetting on the socket connector.



No hole-fill in TH barrel on PCB – Poor Wetting

**Figure 8.9 Poor Wetting on Socket Connector [41]**

Figure 8.10 shows the Wetting Balance test results for the socket connector using the derived settings.  $T_a$ , time to buoyancy, failed using the most stringent settings for  $T_a$ .

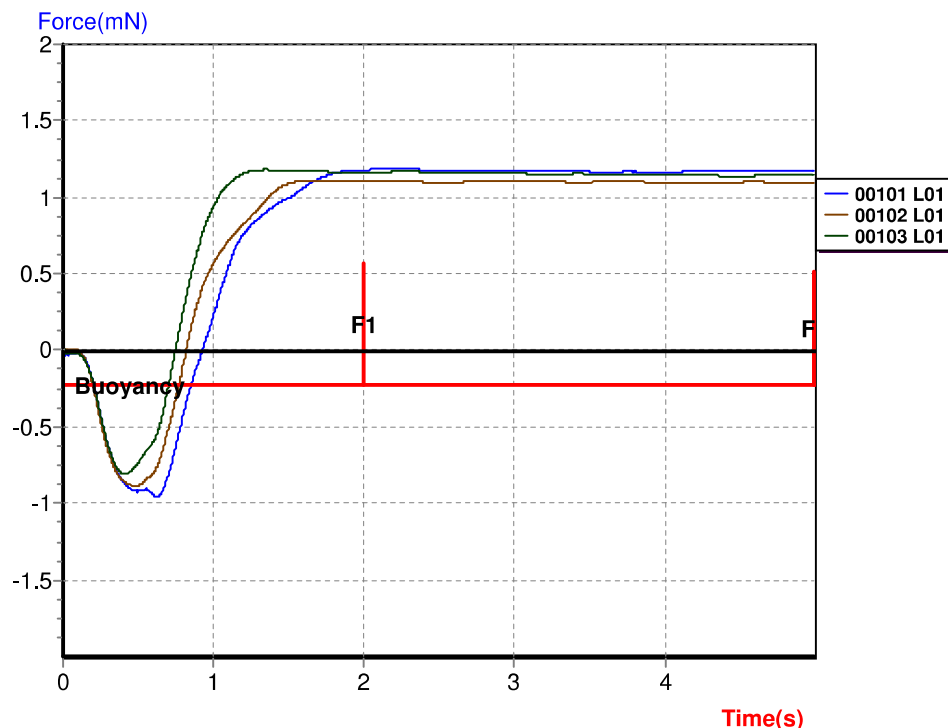
Test Limits and Conditions									
F1	= 0.57 mN @ 2.00 s				F2	= 0.51 mN @ 5.00 s			
$T_a$	= 0.60 s				Buoyancy	= -0.23 mN			
$T_b$	= 1.00 s				Time 2/3 Fmax	= 1.00 s			
Immersion Speed	= 10.0 mm/s				Immersion Depth	= 5.00 mm			
Test Time	= 5 s				Pre-heat Time	= 0 s			
Test Temperature	= 250.0 °C				Flux	= Production Flux			

Description	Results Filename	$T_a$ (s)	$T_b$ (s)	T2/3 (s)	F1 (mN)	F2 (mN)	Fmax (mN)	TFmax (s)	Pass/Fail
SN100C Alloy	00101 L01	0.849	0.927	1.221	1.412	1.402	1.188	2.208	Fail
SN100C Alloy	00102 L01	0.768	0.819	1.119	1.336	1.322	1.112	1.806	Fail
SN100C Alloy	00103 L01	0.702	0.747	0.933	1.391	1.377	1.185	1.335	Fail
Standard Dev		0.074	0.091	0.146	0.039	0.041	0.043	0.437	
Mean		0.773	0.831	1.091	1.380	1.367	1.162	1.783	
Max		0.849	0.927	1.221	1.412	1.402	1.188	2.208	
Min		0.702	0.747	0.933	1.336	1.322	1.112	1.335	

Number of Tests :	003	Passing rate :	0.0 %
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**Figure 8.10 Wetting Balance using Most Stringent Settings**

What has been proven so far for  $T_a$  and  $T_b$  is a 40% difference in results when testing using the lower end (most stringent) as opposed to the higher end (least stringent) of the specification limits as stated within the various international standards. With all the conflicting settings for each of the parameters within the various international standards, solder temperature, immersion speed, and immersion depth, it can be stated that the outcome can vary significantly depending on the combination of settings used.

When these components are used in series production the solderability problems are noticed which is too late because twenty or thirty PCB's could have solderability defects before it is detected. Hundreds or thousands of euros can be spent investigating the root



cause by focusing on the volume of solder paste, the reflow or wave profile and the Wetting Balance results for each component. It is evident the calculated values accomplished using the model equations 7.00 to 7.05 provide a reliable guide for an operator prior to testing any leaded components. The difference is apparent when testing the socket connectors and relays at the least stringent and most stringent settings.

### 8.3.2 Regression Model Verification – Good Solderability Components

For comparison reasons, a component with no solderability problems was also tested, a through-hole LED (light emitting device) component, using the least stringent and most stringent settings. Table 8.5 summarises the Wetting Balance graphs in Appendix 9.13 to 9.17 for the LED component. The average of each of the test results was taken. It should be noted that during some of the testing there was an issue with two of the LED components that were tested using the least stringent settings for Ta and Tb. The LED was contaminated with dry flux and this caused the Ta failures. These two failures were omitted from further analysis. It is immediately evident that a component with no known solderability problems such as the LED, can achieve good Wetting Balance results using the least stringent and most stringent settings. Again similar to the through-hole relays and socket connectors the Fmax values are almost identical but the TFmax values are less than for the least stringent than the most stringent conditions.

**Table 8.5 Results Summary – LED Component**

TH LEDs	Least Stringent Actual	Calculated	TH LEDs	Most Stringent Actual	Calculated
Ta (sec)	0.418	0.467	Ta (sec)	0.507	0.564
Tb (sec)	0.432	0.493	Tb (sec)	0.543	0.623
F1 (mN)	1.357	1.396	F1 (mN)	1.290	1.315
F2 (mN)	1.302	1.360	F2 (mN)	1.279	1.296
Fmax (mN)	1.176	1.424	Fmax (mN)	1.172	1.341
TFmax (sec)	1.097	0.873	TFmax (sec)	1.383	0.935

As was highlighted earlier, the regression model equations are accurate indicators to have and this argument is further enhanced by the results achieved using the LED components. Components of known good solderability will meet the new requirements from the regression models and components of known poor solderability problems will be screened as poor and prevented from being processed in series production.

### 8.4 Shear Test Results – Good vs. Poor Solderability

The solder joint strength was discussed earlier in the project, Section 2.2.9. A comparison of shear test results between large capacitors and small capacitors in SAC305, SN100C and SnPb highlighted that on average the results are comparable between all three alloys. This

section will show the shear test results between the socket connector, through-hole relays and the LED, all of which had similar size leads,  $0.9 \pm 0.1\text{mm}$  but had poor soldering and good soldering results from the Wetting Balance machine. A sample of each component from the same batch was soldered to a PCB and assessed using a shear test machine. Table 8.6 is an overview of these results.

**Table 8.6 Shear test results – Good vs. Poor Solderability SN100C**

Component Type	Shear Test 1 (N)	Shear Test 2 (N)	Shear Test 3 (N)	Shear Test 4 (N)	Shear Test 5 (N)	Min (N)	Max (N)	Average (N)
Socket Connector	85.3	82.3	78.9	83.9	77.8	77.8	85.3	81.6
Through Hole Relay	87.3	81.2	79.4	76.1	85.9	91.2	99.4	82.0
LED Component	111.4	107.8	105.5	107.1	107.2	107.1	111.4	107.8

It is evident from Table 8.6 the different shear test results between a good soldering component and a component with poor soldering characteristics. For a good soldering component the solder alloy wetted to the LED component lead and PCB termination forming a robust solder joint providing the higher shear test results. The opposite is evident for poor soldering components. With less solder wetting to the component leads and PCB terminations due to poor soldering characteristics there is less shear force required to remove the solder joint formation.

## 8.5 Contact Angle Results – Good vs. Poor Solderability

As discussed in Section 2.4.4, the Contact Angle is a significant criterion for any solder joint solderability characteristic. Once the vertical force is known,  $F_{\text{max}}$ , the Contact Angle can be calculated by rearranging Equation 2.4:

$$F = \gamma p \cos\theta - g \rho v \dots \text{Eq-2.4 [56]}$$

Where:

$F$  = maximum force (mN)

$\gamma$  = surface tension of the molten solder under flux (mN/mm)

$p$  = specimen perimeter (mm)

$g$  = gravitational acceleration ( $9.81\text{m/s}^2$ )

$\rho$  = molten solder density ( $\text{g/mm}^3$ )

$v$  = specimen immersed volume (mm)

$\theta$  = Contact Angle ( $^\circ\text{C}$ )

For the Contact Angle the rearranged equation now becomes:

$$\cos \theta = \frac{F}{P} + g \cdot V \dots \text{Eq-8.1}$$

The Contact Angle will be calculated for all three components, LED, through-hole Relay and Socket Connector, using Equation 8.1 and the Fmax results for the most stringent settings in Tables 8.3, 8.4 and 8.5.

### 8.5.1 Through Hole Relay Contact Angle

From Table 8.3 the most stringent setting for Fmax was 1.111mN. The requirement is to have  $\cos \theta$  between 0 and 1 and preferably as close to 1 as possible. The Contact Angle was calculated using this value and the following:

$$F = 1.111\text{mN}$$

$$\gamma = 0.5\text{mN/mm}$$

$$p = 2.83\text{mm}$$

$$g = 0.009.81\text{mm/s}^2$$

$$\rho = 7.4\text{g/mm}^3$$

$$v = 3.18\text{mm}$$

$$\cos \theta = \frac{1.111}{(0.5 \times 2.83)} + (0.00981 \times 7.4 \times 3.18)$$

$$\cos \theta = 1.016$$

### 8.5.2 Through Hole Socket Connector Contact Angle

From Table 8.4 the most stringent setting for Fmax was 1.142mN.

$$\cos \theta = \frac{1.142}{(0.5 \times 2.83)} + (0.00981 \times 7.4 \times 3.18)$$

$$\cos \theta = 1.038$$

### 8.5.3 LED Contact Angle

From Table 8.5 an Fmax value of 1.172mN for the most stringent test was achieved. A Contact Angle is calculated as follows:

$$\cos \theta = \frac{1.172}{(0.5 \times 2.83)} + (0.00981 \times 7.4 \times 3.18) \dots \text{Eq-8.1}$$

$$\cos \theta = 1.05$$

All three Contact Angles are outside the requirement of between 0 and 1 but they are close to 1 indication good wetting. The difference between the 3 components tested, Socket Connector, TH Relay and LED are the times, Ta and Tb, to solder.

## 8.6 Conclusions

Chapter 7 had described and verified the six model equations using 0.9mm diameter copper wires for each of the responses Ta, Tb, Fmax, TFmax, F1 and F2. In this Chapter, the model equations are developed further and a numerical analysis performed to establish the linear relationships such as;

- Time to buoyancy (Ta) – Solder temperature and immersion depth
  - As the immersion depth increases there is an increase in time to reach buoyancy. A low solder temperature of 250°C gives longer Ta results than at a 260°C temperature. The requirement is to have test conditions that will result in the longest possible time to ensure poor soldering components are screened from entering the production floor. The plot in Figure 8.1 represents the relationship for both temperatures and immersion depths. From this plot it is now concluded that the model Equation 7.00 generated is to be used for a Ta prediction.

$$Ta_{\text{predicted}} = C - 0.00753 T_s + 0.00222 I_s + 0.0148 I_D \dots \text{Eq-7.00}$$

Where:  $T_s$  = Solder Temperature (°C)

$I_s$  = Immersion Speed (mm/sec)

$I_D$  = Immersion Depth (mm)

$C$  = Constant = 2.35

The current IPC specification limit for Ta of  $\leq 0.6$ seconds is by far too lenient and should be reviewed by the IPC committee because it is currently not capable of screening out poor soldering components.

- Time to reach the zero line (Tb) – Solder temperature and immersion depth
  - Similar to Ta, a low solder temperature of 250°C gives longer Tb results than at a 260°C temperature. Again the requirement is to have machine settings that will ensure the longest possible time is achieved in order to screen out poor soldering components from production. The plot in Figure 8.2 represents the relationship for both temperatures and immersion depths. It can be stated from analysing this plot that Equation 7.01 is to be used for Ta prediction.

$$Tb_{\text{predicted}} = C - 0.00788 T_s + 0.00111 I_s + 0.0284 I_D \dots \text{Eq-7.01}$$

$C$  = Constant = 2.44

The current IPC specification limit of  $\leq 1$  second is again too lenient and will need to be reviewed by the IPC committee because it is currently not capable of screening out poor soldering components.

- Maximum force (Fmax) – Immersion speed and immersion depth
  - Increasing the immersion depth from 3mm to 5mm at a constant optimum speed of 5mm/sec increases the Fmax result. A high Fmax indicate good soldering. However, in order to be capable of ensuring only high-quality soldering components enter the production area, the requirement is to have Wetting Balance machine parameter settings that will ensure the smallest force possible is achieved by testing components. From Figure 8.3 it can be concluded that Equation 7.03 should be used as a model when predicting the outcome prior to testing a component.

$$F_{\max} = C + 0.00142 I_s - 0.0413 I_D \dots \text{Eq-7.02}$$

$$C = \text{Constant} = 1.21$$

Using the formula in the standard J-STD-002C the Fmax value is calculated to be 1.24mN compared with 1.09mN, which was found when using the Equation 7.02. The IPC target value of 1.24mN is higher than predicted value in this project of 1.09mN. However the target value using the model equation 7.02 is based on the most stringent optimum settings that are used to give the worst possible machine parameter settings for the Wetting Balance machine. The IPC Formula 8.12;

$$F_{\max} = [0.5P - 0.07V] \dots \text{Eq-8.12}$$

is based on the density of the alloy and the volume of component lead immersed in the solder. However, it does not consider immersion speed, which has a significant impact on the results for Fmax as the investigations in this project have shown (Section 6.4.1). For this reason, Equation 7.02 must be considered as an alternative formula for calculating Fmax in an SN100C alloy.

- Force reach after two seconds (F1) – Immersion speed and immersion depth
  - Increasing the immersion depth increases the force reached at two seconds. The high immersion speed of 15mm/sec gave values greater than the speed of 5mm/sec. A high force reading indicates good soldering. However, in order to be capable of ensuring only high-quality soldering components enter the production area, the requirement is to have Wetting Balance machine parameter settings that will ensure the smallest force possible is achieved by testing components. From Figure 8.4, which shows the linear

relationship, it can be concluded that Equation 7.04 should be used as a model when predicting the outcome prior to testing a component.

$$F1_{\text{predicted}} = C + 0.00257I_s + 0.0315 I_D \dots \text{Eq-7.04}$$

$$C = \text{Constant} = 1.20$$

The equation given in the J-Standard-002C states the F1 should be 50% of the maximum force, Fmax. This tolerance of 50% is by far too much and should no longer be used when testing using a Wetting Balance machine because there is a high risk poor soldering components will enter the production area.

- Force reached after five seconds (F2) – Immersion Depth
  - Only immersion depth had a significant effect on the force reached after two seconds. Again similar to all force readings, the requirement is to have Wetting Balance machine parameter settings that will ensure the smallest force possible is achieved by testing components. The relationship generated is linear and is seen in Figure 8.5 and from this it is concluded that Equation 7.05 should be used when predicting the outcome of F1.

$$F2_{\text{predicted}} = C + 0.0320 I_D \dots \text{Eq-7.05}$$

$$C = \text{Constant} = 1.20$$

As stated by the J-standard-002C, ‘no less than 90% of F1’ is good indicator to have. However, with the current IPC criteria for F1 set at ‘no less than 50% of Fmax’, the F2 value is then affected because the F1 specification is by far too lenient.

The Contact Angles,  $\text{Cos}\theta$ , were calculated for each of the components, LED, through-hole relay and socket connector. The requirement for good wetting is to have  $\text{Cos}\theta$  between 0 and 1 and preferably as close to 1 as possible. Only the LED achieved this requirement of 0.999. The LED displayed good solderability results. The through-hole relay and socket connector, which had poor solderability results, had Contact Angles of 1.016 and 1.038 respectively.

The optimum settings for the least and most stringent were verified with through-hole relays, socket connectors and LED’s. Both the relays and socket connectors had a history of solderability problems. The results showed significant differences of approximately 40% within the results for each of the responses Ta, Tb, Fmax, TFmax, F1 and F2, when using the least stringent and most stringent settings on all three-component types. To provide a set of parameter settings for the Wetting Balance test that are robust enough to screen out poor solderability components, the most stringent settings should be used. This

research has derived and proven a new set of proposed parameters for the Wetting Balance test, which are more in line with the demands of high quality in the mass manufacturing electronics environment. These parameters are listed in Table 8.2.

**Table 8.2 Most Stringent Settings**

Responses	Factors		
	Solder Temperature (°C)	Immersion Speed (mm/sec)	Immersion Depth (mm)
<b>Ta / Tb</b>	250	10	5
<b>TFmax / Fmax / F1 / F2</b>	250	5	3

It is concluded from this chapter that the model equations developed by an in-depth design of experiments using 0.9mm diameter copper wires in Chapter 7, will screen out poor solderability through-hole components. The most stringent settings, still within the specification guidelines of J-STD-002C, are reliable and robust for an operator to use when testing through-hole components. When testing through-hole components of known solderability issues such as the relay and socket connector with the most stringent settings, all leads failed. This test was again repeated on LED components that had no record of solderability issues, and all leads passed. All leads on the relays, socket connectors and LED's were approximately the same size in diameter. The model equations derived in Chapter 7 should be used to provide accurate indicators prior to testing along with the settings from Table 8.2.

$$1. T_{a_{\text{predicted}}} = C - 0.00753 T_s + 0.00222 I_s + 0.0148 I_D \quad \dots \text{Eq-7.00}$$

Where C is a constant 2.35

$$2. T_{b_{\text{predicted}}} = C - 0.00788 T_s + 0.00111 I_s + 0.0284 I_D \quad \dots \text{Eq-7.01}$$

Where C is a constant 2.44

$$3. F_{\text{max}} = C + 0.00142 I_s - 0.0413 I_D \quad \dots \text{Eq-7.02}$$

Where C is a constant 1.21

$$4. TF_{\text{max}_{\text{predicted}}} = C - 0.00427 I_s + 0.0312 I_D \quad \dots \text{Eq-7.03}$$

Where C is a constant 1.05

$$5. F1_{\text{predicted}} = C + 0.00257I_s + 0.0315 I_D \quad \dots \text{Eq-7.04}$$

Where C is a constant 1.20

$$6. F2_{\text{predicted}} = C + 0.0320 I_D \quad \dots \text{Eq-7.05}$$

Where C is a constant 1.20

Where:  $T_s$  = Solder Temperature ( $^{\circ}\text{C}$ )

$I_s$  = Immersion Speed (mm/sec)

$I_D$  = Immersion Depth (mm)

C = Constant

These results can be used when setting up the program for the 'Pass'/'Fail' criteria on the MUST II. More importantly however, it could form part of an assessment to help predict the solderability characteristics of through-hole components with a lead diameter  $0.9\text{mm} \pm 0.1\text{mm}$  and provide an expected result before testing using the Wetting Balance machine with an SN100C alloy. This research has highlighted weaknesses in the IPC standards and therefore would recommend that these weaknesses be addressed using the parameters derived in the thesis.



## Chapter 9 Discussion

The objective of this thesis was to investigate and analyse the two main solderability test methods, namely the Dip & Look and Wetting Balance tests, to try and understand the reliability and repeatability of each and also assess the impact the main factors had on each of the responses. The current specification for each response is stated in the various international standards as; Ta is to be reached within 0.6seconds, Tb to be reached within 1 second, F1 the requirement is no less than 50% of Fmax and finally F2 the requirement is no less than 90% of F1. There is currently no known specification for Fmax and TFmax.

What has effectively been put forward are mathematical equations that predict the outcome for each of the responses when using the Wetting Balance test to assess the soldering ability of through-hole components with lead diameters of 0.9mm  $\pm$ 0.1mm in an SN100C alloy. Due to the variation of the parameter settings within the international standards such as J-STD-002C, JESD22-8102D, IEC68-2-69, and IEC68-2-54, the likelihood of diverse Wetting Balance solderability results occurring between component supplier testing and customer testing is highly probable. However, by using the response model equations generated in this thesis, it is now possible to calculate a result for each of the aforementioned responses using the range of settings for each of the factors. It is essential that the significant factor settings used by the component supplier to assess the Wetting Balance test results are known and the system is both stable and repeatable in operation. The expected calculated values can be determined and the results compared with the actual tested results. In order to achieve reliable and repeatable models equations a series of design of experiments were conducted. Having achieved steady state conditions, it was possible to employ design of experiments to indicate the critical factors that require measuring and generate the model equations for each response taking in account the significant factors.

In applying the above methods, the Dip & Look test was initially investigated using Quad-Flat-Pack (QFP) components. QFP's had a long history of having poor solderability with the major defect being no solder-joint formation on corner pins. At the time of the investigations into the Dip & Look test, suppliers of the QFP's were using this test as their main solderability test. By applying Deming's PDCA (Plan-Do-Check-Act) system of process improvement to structure the design of experiments, both the tin/lead and lead-free soldering processes (SAC305 and SN100C) were tested using the QFP leads and also different finish PCB's (HASL SnPb, NiAu, and HASL Pb-free) with the range of settings from the various international standards. The 95% threshold level was achieved for each array of runs from the DoE using different batches of QFP's. Using a preconditioning on

the components had no effect on the 95% coverage target. The only instance for which a defect was achieved was by reducing the solder temperature to a point just above its liquidus for each of the alloys. At this point the solder temperature was too low to encourage wetting of the QFP lead and therefore a failure resulted. Even by its nature the Dip & Look test inspection criteria is very subjective and offers no level of confidence in detecting poor solderability components for a company who solder millions of components daily.

The Wetting Balance method is theoretically based as it tests for wetting time and wetting force – two important factors not investigated when using the Dip & Look method. The force and time results are in milli-newtons and seconds respectively so the precision and repeatability of the Wetting Balance machine is of paramount importance to ensure accurate results. For this reason a repeatability study was carried out on the Wetting Balance machine. This also benefits reducing the soldering ability variation that could be evident on component leads, 20mm lengths of 0.9mm diameter copper wires coated with SN100C solder were used. [85] The reason for coating the bare copper wire was to reduce the thermal effect soldering onto bare copper would have. [85] Using Upper Specification Limits (USL) and Lower Specification Limits (LSL) of 0.6 and 0.3 respectively, a  $C_p$  of 2.02 and a  $C_{pk}$  value of 1.37 are achieved. These values meet the machine capability requirement of  $\geq 1.33$  and at this point further analysis was required to understand and eliminate the unstableness in the graphs. The forces at two seconds (F1) and at five seconds (F2) were then analysed and it was concluded that the range between F1 and F2 for each run was 0.25mN, which was of was very high. The location of the Wetting Balance machine proved to be the critical. Vibrations from machines such as the X-RAY and the SMT line affected the readings from the Wetting Balance machine. This was verified when all other equipment within the vicinity of the Wetting Balance machine was powered off and the test repeated.

The range of values between F1 and F2 reduced significantly to 0.037mN during the three seconds test time. The elimination of vibrations is of paramount importance when developing a stabilised system for testing the solderability using a Wetting Balance machine due to the small margin for error.

A screening Design of Experiments (DoE) for a SN100C alloy with standard production flux determined that the critical factors were solder temperature, immersion speed and immersion depth. Removal speed and dwell time did not have any significant effect on any of the responses and were therefore eliminated from any further investigations. Given the fact that the longest test time based on the responses is five seconds, F2, a longer test time

would not affect the test because all results would be recorded in the five-second timeframe. Similar for removal speed, this is the speed by which the test specimen is removed after the testing is complete, so no affect is possible on any of the results.

Following this screening DoE, a theoretical analysis using a more detailed DoE with an SN100C alloy was assigned using the three factors; solder temperature, immersion speed and immersion depth at three levels, minimum, intermediate, and maximum. Three replicates and three repetitions were carried out given a total of 243 runs. The average of the three repetitions was calculated for a more accurate reading. Using Minitab, Analysis of Variance (ANOVA) tables were generated for each response to determine the significant factors and also the affects of the factors on each of the responses that were assessed.

The Main Effects and Interaction Plots established that the higher solder temperature of 260°C, an immersion speed of 15mm/sec and an immersion depth of 3mm were all common in achieving the least stringent results for the responses time to buoyancy, Ta, and time to reach the zero line, Tb. The reason for establishing two sets of results for each response, least stringent and most stringent, was to highlight the range of results that can be achieved testing within the range of settings from the international standards.

The requirement is to have the force value as high as possible to indicate good wetting. The more solder that attracts to the component the heavier the component weight and therefore the greater the pull force on the clip holder of the Wetting Balance machine. For these three time responses, Ta, Tb, and TFmax, the requirement is to reach the relevant targets in the quickest time possible indicating good wetting. However the target in the project was to develop Wetting Balance machine parameters that would ensure the lowest possible force results and the longest possible time results were in place. This would ensure components of poor solderability would be screened during batch testing after new deliveries are received from component suppliers.

A solder temperature setting of 250°C, an immersion speed of 10mm/sec and an immersion depth of 5mm were optimum settings to achieve the most stringent values for Ta and Tb, i.e. the longest times to reach the respective specification targets, 0.6 seconds and 1 second based on the international standards. To achieve the least stringent results, quickest time possible to reach Ta and Tb, a solder temperature setting of 260°C, an immersion speed of 15mm/sec and an immersion depth of 3mm were optimum.

The time to reach the maximum force, TFmax, had only one significant factor, solder temperature. Again similar to Ta and Tb, the high setting of 260°C resulted in the quickest time while the low temperature setting of 250°C gave slowest time value.

The explanation for these results are due to the fact that at a 260°C temperature for SN100C, the solder has a low viscosity which aids the flow of solder to wet and form a joint. At 250°C the viscosity is increased thus restricting the flow of the solder. The shorter immersion depth of 3mm gave the shortest time results because the shorter depth resulted in less area for the solder to cover than with a 5mm immersion depth. The high immersion speed of 15mm/sec also contributed towards faster times than with a 10mm/sec speed. Reaching the 3mm depth at an immersion speed of 15mm/sec is quicker than reaching a 5mm immersion depth at 10mm/sec and from this the quicker times were explained.

For the three force responses, maximum force ( $F_{max}$ ), force after two seconds ( $F_1$ ) and force after five seconds ( $F_2$ ), the requirement is to have the highest force results possible indicating good wetting as mentioned earlier. There were no common settings between each of these three force responses.

For  $F_{max}$ , a 5mm/sec immersion speed was optimum for the least stringent and most stringent results. This low speed, when making initial contact with the coated copper wire would not repel the solder as much as it would when at a high immersion speed of 15mm/sec. At a 5mm immersion depth the coated copper wire is immersed deeper into the solder than at a 3mm depth and because of this a greater volume of solder is available to wet to the coated copper wire and reach a higher maximum force.

The immersion speed and immersion depth were critical factors for the force reached after two seconds ( $F_1$ ) but after another three seconds of testing, when  $F_2$  was reached, only the immersion depth became the critical factor. Using an immersion speed of 15mm/sec and an immersion depth of 4mm, high force results were achieved for  $F_1$  than with a speed of 5mm/sec and a depth of 3mm. When the solder bath initially makes contact with the coated copper wire at 15mm/sec, two seconds must pass before  $F_1$  is recorded which provides sufficient time for the solder to settle after the turbulent contact at the high speed and immediately start to wet even before the 4mm depth is achieved. The same observation can be made for  $F_2$ , but with the low immersion speed, 5mm/sec, and shorter immersion depth of 3mm, less area is presented for the solder to attract to and therefore less force required in achieving its highest force result after five seconds.

Chapter 7 and 8 develops and utilises mathematical models for each of the responses by use of Minitab. Each mathematical model is tested using the optimum settings for the least and most stringent settings and compared with the actual test results. It is evident that the predicted results using the model equations generated by Minitab, (7.00 to 7.05) for the least stringent and most stringent settings are accurate indicators to have before commencing any testing and this is evident from Table 7.13.

Subsequent analysis of the models showed that a linear relationship exists between all of the responses and the factors. The strength of the relationship was ascertained by the  $R^2$  values. The optimum settings for the model equations were verified with through-hole relays, socket connectors and LED components, all of diameters  $1\text{mm} \pm 0.1\text{mm}$ . Both the relays and socket connectors had a history of solderability problems. XRF verified the plating thickness on the leads as being uniform. The Wetting Balance tests conducted on the relays and socket connectors using the least stringent settings and all passed the J-STD-002C specification for Ta ( $<0.6$  seconds) and Tb ( $<1$  second) and this can be seen in the actual results in Tables 8.3 and 8.4. However, the same relays and socket connectors from the same batch were tested using the most stringent settings and all failed the international specification requirements for Ta ( $<0.6$  seconds) and Tb ( $<1$  second).

For comparison reasons, an LED component with no history of solderability problems was tested using the least and most stringent settings and the specification requirements were achieved. It is immediately evident that a component with no known solderability problems such as the LED, can achieve good Wetting Balance results using the least stringent and most stringent settings.

The model equations developed by an in-depth design of experiments using  $0.9\text{mm}$  diameter copper wires in Chapter 7, will screen out poor solderability through-hole components with lead diameters  $0.9\text{mm} \pm 0.1\text{mm}$ . The most stringent settings, still within the specification guidelines of J-STD-002C, are reliable and robust for an operator to use when testing through-hole components.

However it must be noted that the method of calculating predicted F1 results in the international standard, J-STD-002C, is by far too lenient. F1 is calculated by getting 50% of the maximum force and F2 is calculated based on 'no less than 90% of F1'. The model equations generated in this thesis, not only for F1 and F2, but also for Ta, Tb, Fmax and TFmax, reduce the specification requirements and increase the efficiency of the Wetting Balance test.

## Chapter 10 Conclusions and Recommendations

### 10.1 Conclusions

1. The Dip and Look solderability test method serves no purpose in determining a component or PCB's ability to solder due to the fact that all experimental runs from the design of experiments conducted in the project achieved the 95% solder coverage specification limit.
2. Even using extreme ageing conditioning by the use of pre-conditioning processes, Dry baking and Steam, all component still passed the 95% threshold level.
3. Using a bare copper wire and a copper wire coated with the relevant alloy can affect the results significantly. [85]
4. 20mm lengths of copper wire were the optimum for providing more accurate results than a 40mm length. The results were far more stable with a 20mm length because of the heat conduction with copper. [85]
5. The location of the Wetting Balance machine is a critical point that must be considered prior to testing. Vibrations from machines such as the X-RAY and the SMT line affected the readings. This was proved when all other equipment within the vicinity of the Wetting Balance machine was powered off and the test repeated. The graphical lines on the Wetting Balance curve showed better stability with the surrounding equipment powered off.
6. The significant factors that affected the responses,  $T_a$ ,  $T_b$ ,  $F_{max}$ ,  $TF_{max}$ ,  $F_1$  and  $F_2$  were solder temperature, immersion speed and immersion depth. Dwell time and removal speed did not have any affect.
7. For  $T_a$  and  $T_b$ , solder temperature, immersion speed and an interaction between immersion speed and immersion depth had a significant effect.
8. For  $F_{max}$ , immersion depth was the only significant factor highlighted, however, the interaction between immersion speed and immersion depth was also considered because of the p-value.
9. For  $TF_{max}$ , solder temperature is the only factor that presented an effect of the time to reach the maximum force.
10. For  $F_1$  and  $F_2$ , solder temperature and immersion depth both showed significant effects on the forces at 2 and 5 seconds.
11. Also when conducting the experiment it was noted that the speed setting of 25mm/sec seemed to be too fast for the Wetting Balance and for all the array of runs with an immersion speed of 25mm/sec, the array was repeated a number of

times before the copper wire was immersed into the solder. Gen3 systems, supplier of the machine, were unable to explain why this was happening. In order to prevent an occurrence of this error, the maximum speed for the detailed DoE will be set to 15mm/sec. By doing a quick trial, 15mm/sec seemed to be the optimum speed for the Wetting Balance machine.

12. Tables 10.1 and 10.2 summarise the optimum least and most stringent settings.

**Table 10.1 Least Stringent Settings**

Responses	Factors		
	Solder Temperature	Immersion Speed	Immersion Depth
	(°C)	(mm/sec)	(mm)
<b>Ta / Tb</b>	260	15	3
<b>TFmax / Fmax</b>	260	5	5
<b>F1 / F2</b>	260	15	4

**Table 10.2 Most Stringent Settings**

Responses	Factors		
	Solder Temperature	Immersion Speed	Immersion Depth
	(°C)	(mm/sec)	(mm)
<b>Ta / Tb</b>	250	10	5
<b>TFmax / Fmax / F1 / F2</b>	250	5	3

13. A solder temperature of 260°C, an immersion speed of 15mm/sec and immersion depths of 3mm and 4mm are all common in achieving good soldering ability and are considered to be the least stringent.

14. With a solder temperature of 250°C, an immersion speed of 10mm/sec and immersion depths of 3mm and 5mm are considered the most stringent settings.

15. Ta and Tb have identical settings for the least and most stringent tests.

16. For Fmax, 5mm/sec is the optimum speed and the immersion depth of 3mm and 4mm are the difference between the least and most stringent respectively.

17. Mathematical models were generated to predict each of the responses at the least stringent and most stringent settings and also show linear relationships.

i. For Time to buoyancy (Ta) – Solder temperature and immersion depth

As the immersion depth increases there is an increase in time to reach buoyancy. A low solder temperature of 250°C gives longer Ta results than at a

260°C temperature. The requirement is to have test conditions that will result in the longest possible time to ensure poor soldering components are screened from entering the production floor. The relationship between solder temperature and immersion depth is represented in Figure 8.1. From this plot it is now concluded that the model Equation 7.00 generated, is to be used for a Ta prediction

$$Ta_{\text{predicted}} = C - 0.00753 T_s + 0.00222 I_s + 0.0148 I_D \dots \text{Eq-7.00}$$

Where:  $T_s$  = Solder Temperature (°C)

$I_s$  = Immersion Speed (mm/sec)

$I_D$  = Immersion Depth (mm)

$C$  = Constant = 2.35

- ii. The current IPC specification limit for Ta is  $\leq 0.6$  seconds. This tolerance band is by far too wide and must be reviewed by the IPC committee because it is currently not capable of screening out poor soldering components.

18. For Time to reach the zero line (Tb) – Solder temperature and immersion depth

Similar to Ta, a low solder temperature of 250°C gives longer Tb results than at a 260°C temperature. Again the requirement is to have machine settings that will ensure the longest possible time is achieved in order to screen out poor soldering components from production. The relationship between solder temperature and immersion depths is represented in Figure 8.2. From this plot the Equation 7.01 is to be used for Ta prediction.

$$Tb_{\text{predicted}} = C - 0.00788 T_s + 0.00111 I_s + 0.0284 I_D \dots \text{Eq-7.01}$$

$C$  = Constant = 2.44

- iii. The current IPC specification limit for Tb is  $\leq 1$  second. Again this tolerance band is too wide and needs to be reviewed by the IPC committee because it is currently not capable of screening out poor soldering components.

19. Maximum force (Fmax) – Immersion speed and immersion depth

Increasing the immersion depth from 3mm to 5mm at a constant optimum speed of 5mm/sec increases the Fmax result. This linear relationship is represented in Figure 8.3. A high Fmax indicate good soldering. However, in order to be capable of ensuring only high-quality soldering components enter the production area, the requirement is to have Wetting Balance machine parameter settings that will ensure the smallest force possible is achieved by testing components. From Figure 8.3 it



can be concluded that Equation 7.03 should be used as a model when predicting the outcome prior to testing a component.

$$F_{\max} = C + 0.00142 I_s - 0.0413 I_D \dots \text{Eq-7.02}$$

$$C = \text{Constant} = 1.21$$

- iv. Using the formula from standard J-STD-002C the  $F_{\max}$  value is calculated to be 1.24mN compared with 1.09mN, which was found when using the Equation 7.02. The IPC target value of 1.24mN is higher than predicted value in this project of 1.09mN. However the target value using the model equation 7.02 is based on the most stringent optimum settings that are used to give the worst possible machine parameter settings for the Wetting Balance machine. The IPC formula 8.12;

$$F_{\max} = [0.5P - 0.07V] \dots \dots \dots \text{Eq-8.12}$$

is based on the density of the alloy and the volume of component lead immersed in the solder. However, it does not consider immersion speed, which has a significant impact on the results for  $F_{\max}$  as the investigations in this project, has shown. For this reason, Equation 7.02 must be considered as an alternative formula for calculating  $F_{\max}$  in an SN100C alloy.

#### 20. Force reached after two seconds (F1) – Immersion speed and immersion depth

Increasing the immersion depth increases the force reached at two seconds. The high immersion speed of 15mm/sec gave values greater than the speed of 5mm/sec. A high force reading indicates good soldering. However, in order to be capable of ensuring only high-quality soldering components enter the production area, the requirement is to have Wetting Balance machine parameter settings that will ensure the smallest force possible is achieved by testing components. From Figure 8.4, which shows the linear relationship, it can be concluded that Equation 7.04 should be used as a model when predicting the outcome prior to testing a component.

$$F1_{\text{predicted}} = C + 0.00257 I_s + 0.0315 I_D \dots \text{Eq-7.04}$$

$$C = \text{Constant} = 1.20$$

- a. The equation given in the J-Standard-002C states the F1 should be 50% of the maximum force,  $F_{\max}$ . This equation is by far too lenient and is not a good reference to have when trying to get a predicted value. Component users when testing using a Wetting Balance machine should no longer use the current standard

of 50% because there is a high risk that poor soldering components will enter the production area.

21. Force reached after five seconds (F2) – Immersion Depth

Only immersion depth had a significant effect on the force reached after two seconds. Again similar to all force readings, the requirement is to have Wetting Balance machine parameter settings that will ensure the smallest force possible is achieved by testing components. The relationship generated is linear and is seen in Figure 8.5 and from this it is concluded that Equation 7.05 should be used when predicting the outcome of F1.

$$F2_{\text{predicted}} = C + 0.0320 I_D \dots \text{Eq-7.05}$$

$$C = \text{Constant} = 1.20$$

22. As stated by the J-standard-002C, ‘no less than 90% of F1’ is good indicator to have. However, with the current IPC criteria for F1 set at ‘no less than 50% of Fmax’, the F2 value is then affected because the F1 specification is by far too lenient.

This research has highlighted weaknesses in the IPC standards and therefore would recommend that these weaknesses would be addressed using the parameters derived in the thesis.

## 10.2 Recommendations

1. Remove the Dip and Look test from all component and PCB suppliers as a means of assessing the soldering ability. The analysis compiled in Chapter 3 showed the Dip and Look test serves no purpose in testing a component of PCB's soldering ability.
2. Determine the impact of noise such as vibration and radio frequency on the performance of the Wetting Balance machine to assess its impact on the results. It was seen in this thesis that the impact of external influences such as the X-Ray machine affects the results from the Wetting Balance machine. A concise analysis into these affects is required so they are understood and eliminated as much as possible.
3. Extensive testing is required on the solder globule method using a different test specimen other than a copper wire. Reason is the globule method is more suited to smaller SMT components.
4. Review the current Wetting Balance requirements in the international standards and set more stringent test criteria for different component types. The current criteria are too lenient for components to adhere to. The risk of poor solderability components entering a series production line is high due to the current criteria. For example, the responses  $T_a$ ,  $T_b$ ,  $F_{max}$ ,  $F_1$  and  $F_2$  each have specifications listed in the various international standards. These specifications are similar for all components types tested using different alloys. This project has highlighted the fact that components with lead diameters of  $1\text{mm} \pm 0.1\text{mm}$  with known solderability issues will pass the specifications set out in these standards.

## Chapter 11 References

1. Salam, B., Ekere, N. N., Durairaj, R., 'A Study of Intermetallic Compounds (IMC) formation and growth in Ultra-Fine pitch Sn-Ag-Cu lead-free solder-joints', Electronics System integration Technology Conference, Dresden, Germany, 2006.
2. Tong, J. P. C., Tsung, F., Yen, B. P. C., 'A DMAIC approach to printed circuit board quality improvement', International advanced Manufacturing Technology, 2004.
3. Perez-Bergquist, A. G., Fang, C., Perez-Bergquist, S. J., Lopez, M.F., Trujillo, C. P., Cerreta, E. K., Gray, G. T., 'The constitutive response of three solder materials' in Journal of Alloys and compounds, Volume 524, 25 May 2012, Pages 32 – 57.
4. Woods, R., Gillick, Dr. C., 'Investigate the Dip and Look test procedure for components in a Pb and Pb-free soldering process'. Proceedings of the 24<sup>th</sup> International Manufacturing Conference, IMC24, Waterford Institute of Technology, 2007, pg. 937 – 944.
5. Park, J. Y., Jung, J. P., September 1999. The analysis of the withdrawal force curve of the wetting balance curve. Components and Packaging Technologies, IEEE Transactions on Volume 22, Issue 3, Pages: 372 – 377.
6. Matsumoto, T., and Nogi, K., 'Wetting in Soldering and Microelectronics'. Annual Review of Materials Research Vol. 38: 251-273, March 20, 2008.
7. IPC/ECA J-STD-002C Solderability Test for Component Leads, Terminations, Lugs, Terminals and Wires, December 2007.
8. Wassink, R. J. K., 'Soldering in Electronics, Electrochemical Publications Ltd., 1989, pg. 301.
9. Testerion joins the Million Dollar Club, in Dataweek, Electronics and Communication Technology, February 2012.
10. Theriault, M., Blostein, P., 'Nitrogen and Soldering: Reviewing the issue of Inerting', SMT Magazine – PCB Outsourcing: Technology and business Focus, June 2000.
11. Puttlitz, Karl J. Overview of Lead-Free Solder Issues Including Selection, in: Handbook of Lead-Free Solder Technology for Microelectronic Assemblies, pg 9, 2004: Edited by; Karl J. Puttlitz and Kathleen A. Stalter. IBM Corporation, New York, U.S.A.
12. Manko, Howard H., 2001. Solders and Soldering, pg 5. 4th Ed., McGraw-Hill, Two Penn Plaza, NY.

13. Lea, C., 1988. 'A Scientific Guide to Surface Mount Technology', Electrochemical Publications Limited pg. 309, 1988.
14. Schouten, G., 2004. 'Relationship between surface tension, wetting force and capillary force', Vitronics Soltec – A Dover Company, August 2004.
15. [www.efunda.com/glossary/units/units-surface\\_tension\\_newton\\_per\\_meter.cfm](http://www.efunda.com/glossary/units/units-surface_tension_newton_per_meter.cfm)
16. Kumar, K., 2007. 'Review of non-reactive and reactive wetting of liquids on surfaces', Advances in Colloid and Interface Science, pgs 61 – 89, May 2007.
17. Puttlitz, Karl J., Solderability. In: Handbook of Lead-Free Solder Technology for Microelectronic Assemblies, 2004: Edited by; Karl J. Puttlitz and Kathleen A. Stalter. IBM Corporation, New York, U.S.A, pg 439-442.
18. Willis, B., Guide to PCB solder finishes and process defects, webinar, 2010.
19. Multicore, Must System II. 'Precision solderability testing of conventional and SMD components, PCB pads, and plated-through holes'. Concoat Systems – Measuring Electronics Reliability, 2004.
20. Zhang, Y., Cai, Z., Mustafa, M., Suhling, J. C., Lall, P., Bozack, M. J., The influence of Aging on the stress strain and creep behaviour of SAC solder alloys. IEEE, 2010.
21. [www.gen3systems.com/viewnews-testing\\_times\\_for\\_lead\\_free\\_alloys.php](http://www.gen3systems.com/viewnews-testing_times_for_lead_free_alloys.php)
22. Lea, C., 1993. Solderability and its measurement, Engineering Science and Education Journal, Volume 2, Issue 2, Apr 1993, Pages 77 – 84.
23. Gen 3 System Ltd., Must System, Solderability testing using the Wetting Balance and the Micro-Wetting Balance test methods.
24. Schwartz, M.M., 1993. 'Fundamentals of Soldering'. In ASM Handbook Volume 6, Welding, Brazing, and Soldering (ASM International), 1993, Pages 126 – 137.
25. Wassink, R. J. K., Verguld, M. M. F., 1995. 'Manufacturing Techniques for Surface Mounted Assemblies', Electrochemical Publications Ltd., pg65, 1995.
26. Oh, C., Han, C., Park, N., Song, B., Hong, W., 2009. 'Creep Mechanism Fractography Analysis on SnPb Eutectic Solder Joint Failure'. In IEEE Transactions Microelectronics and Packaging Conference, 15-18 June 2009, Pages 1 – 4.
27. Lea, C., 1988. 'A Scientific Guide to Surface Mount Technology', Electrochemical Publications Limited pg. 379, 1988.
28. Miric, A. Z., Grusd, A., 'Lead-free Alloys. Soldering and Surface Mount Technology', pg. 19-25, 1997.

29. Lee-Cheng, Ning, 'Reflow Soldering Processes and Troubleshooting – SMT, BGA, CSP, and Flip Chip Technologies', pg. 253, 2001.
30. Asahi Chemical Research Laboratory Co., Ltd., 2007, 'ASC-SN100C of SnCuNiGe Alloy Composition', 11<sup>th</sup> July 2007.
31. Nihon Superior, 'SN100C (Sn-Cu-Ni+Ge) – Effect of the addition of Ni and Ge', 2006.
32. Kostal Ireland GmbH, Workmanship Standards, Component Images, 2009.
33. Nihon Superior Ltd., 'Lead-Free Soldering for Environmental Conservation', May 2005.
34. Manko, Howard H., 2001. 'Solders and Soldering', pg 414. 4th Ed., McGraw-Hill, Two Penn Plaza, NY.
35. Chen, C., Chiang, J., Lee, F.Y., 'De-Mystifying material selection for lead-free soldering', pg. 18-22, 2006.
36. Kostal Ireland GmbH SMT Lab., Reflow Oven Template profiles, 2010.
37. Blair, H.D., Pan, T.Y., Nicholson, J.M., Cooper, R.P., Oh, S.W., Farah, A.R., 'Manufacturing Concerns of the Electronic Industry regarding Intermetallic Compound Formation during the Soldering Stage', Ford Motor Company, 1996.
38. Bernasko, P.K., Mallik, S., Elere, N.N., Seman, A., Takyi, G., 'Effect of Reflow Profile and Thermal Cycle Ageing on the Intermetallic Formation and Growth in Lead-Free Soldering', 11th Electronic Packaging Technology Conference, 2009.
39. <http://www.efunda.com/materials/solders/guidelines.cfm>
40. Lee-Cheng, Ning, 'Reflow Soldering Processes and Troubleshooting – SMT, BGA, CSP, and Flip Chip Technologies', pg. 20, 2001.
41. Judd, M., Brindley, K., 'Soldering in Electronics Assembly', pg. 121, Second Edition 1999.
42. Kostal Ireland GmbH SMT Lab, Pin-in-Paste cross section image, 2009.
43. Kostal Ireland GmbH SMT Lab., Solder Joint Strength Analysis, 2011.
44. Wassink, R. J. K., Verguld, M. M. F., 1995. 'Manufacturing Techniques for Surface Mounted Assemblies', Electrochemical Publications Ltd., pg91 - 102, 1995.
45. Hansen, K. S., Jellesen, M. S., Mueller, P., Westermann, P. J. S., Ambat, R., University of Denmark. 'Effect of Solder Flux Residues on Corrosion of Electronics', Department of Mechanical Engineering, University of Denmark, 2009.

46. Schwartz, M. M., Aircraft, S., 'Fundamentals of Soldering', ASM Handbook Volume 6, Welding, Brazing, and Soldering, ASM International, pg. 126-137, 1993.
47. Liukkonen, M., Havia, E., Leinonen, H., Hiltunen, Y., 2008. 'Application of self-organizing maps in analysis of wave soldering process', Expert Systems with Applications, pgs. 4604 – 4609, 2009.
48. Lee, Ning C. Reflow Soldering Processes and Trouble Shooting SMT, BGA, CSP, and Flip Chip Technologies.
49. Coombs, C.F. Jnr., 'Printed Circuits Handbook', Fifth Edition, pg 46.6, 2001.
50. Rahn, Armin, 1993. 'The Basics of Soldering'. John Wiley & Sons, Inc., 605 Third Avenue, NY, pg. 88.
51. Woods, R., Gillick, Dr. C., 'Investigate the Dip and Look test procedure for components in a Pb and Pb-free soldering process'. Proceedings of the 24<sup>th</sup> International Manufacturing Conference, IMC24, Waterford Institute of Technology, 2007, pg. 937 – 944.
52. <http://www.emsnow.com/npps/story.cfm?id=20698>
53. IPC International Standards, 'J-STD-003A. Solderability Tests for Printed Boards', A joint standard developed by the EIA Soldering Technology Committee (STC) and the IPC Printed Wiring Board Solderability Task Group.
54. Lea, C., 1988. A Scientific Guide to Surface Mount Technology; Electrochemical Publications Ltd., pg 353 – 355.
55. Concoat Systems – Measuring Electronics Reliability, 2004. 'Solderability Test System for Surface Mount and Conventional Components', User Manual.
56. IPC, IPC-TM-650 Test Methods Manual, Liquid Flux Activity, Wetting Balance Method, The Institute of Interconnecting and Packaging Electronic Circuits 2215 Sanders Road, Northbrook, IL 60062-6135, 1995.
57. International Standard ISO 12224-3, Wetting Balance Test Method for flux cored solder wire efficiency, 2003.
58. Rosano, H. L., Gerbacia, W., Feinstein, M. E., Swaine, J. W. Jr., February 1971. Determination of the Critical Surface Tension using an Automatic Wetting Balance.
59. Park, Jae Y Jung, Jae, Pil, Kang, Choon S., September 1999. The Analysis of the Wetting Force Curve of the Wetting Balance Curve. In: IEEE Transactions on Components and Packaging Technology, Vol. 22, No. 3,

60. International Standard, IEC-60068-2-54 Environmental Testing – Part 2-54: Tests – Test Ta: Solderability testing of electronic components by the wetting balance method.
61. International Standard, IEC-60068-2-69 Environmental testing of electronic components for surface mount devices by the wetting balance method.
62. JEDEC Solid State Technology Association, JESD-22-B102D Solderability, October 2007.
63. [http://www.loettechnik.com/Concoat/pdf/Must\\_II\\_doc\\_1.pdf](http://www.loettechnik.com/Concoat/pdf/Must_II_doc_1.pdf)
64. Multicore, Must System II. Precision solderability testing of conventional and SMD components, PCB pads, and plated-through holes, User Manual.
65. Robinson, Brett H., 2009. 'E-waste: An assessment of global production and environmental impacts'. Science of the Total Environment, July 2009, Pages 183 – 191.
66. European Parliament and the Council of the European Union, 2002. Directive of the European Parliament and Council of 8 November 2002 on Waste Electrical and Electronic Equipment (WEEE).
67. Lauridsen, Erik H., 2010. 'Sustainable transition of electronic products through waste policy'. Research Policy 39, January 2010, Pages 486 – 494.
68. European Parliament and the Council of the European Union, 2003. Directive 2002/95/EC of the European Parliament and of the Council of 27 January 2003 on the Restriction Of the use of certain Hazardous Substances in electrical and electronic equipment.
69. Parameswariah, C., 2006. 'RoHS – What is it?', IEEE Transactions on Engineering, Volume 25, Issue 2, April 2010, Pages 29 – 30.
70. Eveloy, V., Ganesan, S., Fukuda, Y., Pecht, M.G., 'Are you ready for lead-free electronics?', IEEE Transactions on Components and Packaging Technologies, Volume 28, No. 4, December 2005.
71. ACEA, 2005. 'End of Life Vehicles – Comments of the Automotive Industry on the Directive 2000/53/EC.' Second Edition, September 2005.
72. European Parliament and the Council of the European Union, 2000. Directive 2000/53/EC of the European Parliament and the Council of 18 September 2000 on End of Life Vehicles.
73. European Parliament and the Council of the European Union, 23<sup>rd</sup> February 2010. 'Amending Annex II to Directive 2000/53/EC of the European Parliament and of the Council on end-of-life vehicles'.



74. Fisher, R. A., 'The Design of Experiments', Oliver Boyd, Edinburgh, Scotland, 1935.
75. Telford, J. K., 'A Brief Introduction to Design of Experiments', In Johns Hopkins APL Technical Digest, 224 Volume 27, No. 3, 2007.
76. Schmidh, Steven R., Launsby, Robert G., 2003. 'Understanding Industrial Designed Experiments', 4<sup>th</sup> Edition.
77. Montgomery, D. C., Runger, G. C., 2002. 'Applied Statistics and Probability for Engineers', Third Edition.
78. Greenfield, T., Metcalfe, A., 2007. 'Design and Analyse Your Experiment with MiniTab', 1<sup>st</sup> Edition.
79. Montgomery, D.C., Runger, G. C., Hubele, N. F., 2007. 'Engineering Statistics', 4<sup>th</sup> Edition, August 2007.
80. Pyzdek, T., 2003. 'The Six Sigma Handbook – A Complete Guide for Green Belts, Black Belts, and Managers at All Levels', McGraw-Hill, 2003.
81. Woods, R., 'Analysis of Solderability Test Methods: Prediction Model Generation for Through Hole Components', Design of Experiments, Interaction and Main Effects Graphs, 2012.
82. Woods, R., Gillick, Dr. C., 'A Capability study of a Wetting Balance machine using 0.9mm diameter copper wire'. Proceedings of the 20<sup>th</sup> International Conference on Flexible Automation and Intelligent Manufacturing 2010 Conference, FAIM 2010, California State University Easy Bay, USA, 12<sup>th</sup> July – 14<sup>th</sup> July, 2010, pg. 806 – 813.
83. Kostal GmbH, Process Capability Analysis - LK Procedural Instructions VA 09-37.
84. Kostal GmbH, Raw Material Purchasing Process - LK Procedural Instructions VA 05-73.
85. Woods, R., Gillick, Dr. C., 'The Effect of Testing a Copper Wire and a Copper Wire coated with SnPb solder using a Wetting Balance Test'. Proceedings of the World Congress on Engineering 2010 Conference, WCE2010, London, UK, 30<sup>th</sup> June – 2<sup>nd</sup> July, 2010, pg. 2327 – 2330.
86. Morris, O. D., 'Text and Tests 3, Leaving Certificate Mathematics Ordinary Level.' The Celtic Press, page 44.
87. [http://en.wikipedia.org/wiki/Coefficient\\_of\\_determination](http://en.wikipedia.org/wiki/Coefficient_of_determination)