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Optimized Wire Bond Recipe for 1mil Au Wire on Al Pads of Various Pad Widths

By

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Abstract

The prototype assembly shop in a Semiconductor or IC manufacturing company that must be fast and flexible. The endless variety of IC die, discrete components, test chips, and tiny process control monitor devices all require wire bonding in some package. The bonding technician needs guidance as to which capillary, free air ball size, force, ultrasonic energy, and temperature will work best for the given pad size and package design. There is typically no chance for experimenting or development of an optimal bonding recipe. The technician is expected to quickly bond correctly the first time, and every time, regardless of the part type, bond pad dimensions, or package type. In the past technicians had to go by a "standard" recipe for 25um Au wire ball bond on large pads. This experimental study seeks optimum "first bond" thermosonic ball bonding recipe settings for 25um Au wire on Al bond pads of 50um and larger, for two capillary styles, "high frequency" and "bottleneck". Larger size bond pads permit a larger "nail head" bond which has a much larger shear force than the tiny ball bond that can fit a 50um pad width. Bonding settings need to change drastically between large and small pad sizes. Some packages have only tiny areas near the cavity walls for lead bonding, requiring the use of a thinner bottleneck capillary, for which an optimal first bond recipe had not been developed. SEM photos and bond shear test results for a variety of ball sizes and shapes help to determine optimal settings for reliable ball bonds on various pad sizes. Optimization based on a series of designed experiments maximizes bond strength per contact area for various ball diameters. (Wire looping and other aspects of ball bonding are not addressed here). Recipe tables now provide the needed guidance for the bonding technician to choose an appropriate bonding recipe on each new job they encounters.

Chapter 1

1. Introduction

1.1. Overview

Wire bonding is a method of making interconnections between the semiconductor device and its packaging. During this process small soft metal wire is attached to compatible metal surface usually called as pads. Wire bonding is the most cost-effective and widely used method in semiconductor industry for making interconnections.

During 1970's about one third of the semiconductor device failures were due to wire bonding. Over the time many failure mechanism were identified and changes in bonding techniques and recipes have been made to overcome these failures. Optimization experiments have been made based on metals, pad size and other limiting factors.[1-3] But, there is still a need of further experiments for bonding recipe optimization to increase bond life time and reduce number of failures during bonding. Also there may be a need of study to understand interrelations between different bonding factors in each particular wirebonding situation.

1.1. Problem Statement

Over time the semiconductor industry has progressed very much in reducing the size of the die. With reduction in chip size comes the need of new processes and recipes for smaller ball bonds while maintaining good bonding strength. Reducing ball bond size directly reduces contact area between the two metals, thus reducing bond strength. There

is need of bonding experiments to be done to find optimum recipes that generate small ball bonds, satisfying size and bond strength requirements for bond reliability.

1.2. Objective

There is increasing demand for high reliability of semiconductor products, including the wire bonding during integrated circuit assembly. This thesis is focused on gold wire ball bonding recipe optimization. Ball bonding is a common wire bonding method and gold (Au) wire is preferred because of its high oxidization tolerance and low harshness due to its soft malleable nature. At many Semiconductor industries some traditional wire bonding procedures are in use, but they have not been optimized for bond reliability. Semiconductor industries requests the development of bonding recipe parameters and tooling specifications to routinely accomplish reliable gold wire bonds on various pad aluminum (Al) widths in a few different ceramic package types, some having small cavities. This thesis investigates the most influential wire bonding parameters in terms of the resulting bond reliability for gold wire of 25μm (1mil) diameter through careful design of experiment, measurement and analysis.

This project will required requires a strong knowledge of semiconductor fabrication and assembly processes, metallurgy of Au and Al, and the microelectromechanical operation of a commercial wire bonding machine. Multiple designed experiments were carefully planned to minimize time and resource use. Measurements in micro-dimensions and reliability testing was carried out, with statistical analysis following.

Input factors are: Temperature (Temp), ultrasonic generator current (USG), Bonding force (Force), FAB (Free air ball diameter, in mils) and Capillary Type: High Frequency (HF), or Bottleneck (BN).

Outputs that were measured and analyzed are: NSOP (Non-stick on Pad), Bond Pull Strength, Bond Shear Force, and ball diameter, ball contact area, and ball height.

Chapter 2

2. Literature Review

2.1. Bonding Techniques

Wire bonding processes can be performed using ball bonding, wedge bonding and compliant bonding techniques.

2.1.1. Thermo-compression Bonding

This bonding process involves time, force and heat. The wire is pressed against hot metal surface at high force for some time to achieve bond. Thermo-compression bonding is usually done with gold wire on gold surface.

2.1.2. Ultrasonic Bonding

Ultrasonic bonding involves time, force and ultrasonic energy to make a bond between two metals. This process can be performed with copper, aluminum, gold, palladium, silver & platinum.

2.1.3. Thermo-sonic Bonding

The most widely used and time efficient bonding process involving heat, time, force and ultrasonic energy. The wire is pressed against a hot metal surface at low force and vibrated for short period of time to form the bond. Thermo-sonic Au wirebond is used in this project.

2.2. Bonding factors

There were many influencing factors that control nature of the ball bonds, but 5 major factors were selected based on literature review. These factors and their optimal range along with their effect on bonds are described below.

2.2.1. Temperature

Temperature plays vital role in wire bonding and is one of the most important parameter effecting bond strength. Studies have shown [4] that too low temperature (40-80 °C) results in unsuccessful bonding as lowering temperature reduces intermetallic formation thickness between metals being used, for following experiments gold wire and aluminum pads which results in weak bond strength and more likely cause non-stick on pad (NSOP) and lifted ball bonds[5].

Too high a temperature (320-360 °C) gives rise to over bonding phenomena, decreasing bonding strength due to degradation of interface. Moreover high temperature (> 300 °C) results in some of well-known failures like “Purple plague”. The term comes from the color of the $AuAl_2$ intermetallic compound formation that occurs around the perimeter of the Au-Al bond [6]. High temperature promotes thicker intermetallic compound (IMC) formation and sometimes when the pad Al is thin it could be destructive to have thick IMC [7]. Use of high temperature in wire bonding could be damaging to plastic packaging material so selection of temperature is not only dependent on wire and pad specifications but the package and the material beneath the pad so the bonding process does not damage the product during fabrication. Satisfied and stable bonding can be attained only when temperature is in moderate region (180-220 °C).

2.2.2. Ultrasonic Generator (USG)

Ultrasonic generator parameter refers to ultrasonic welding mechanism. Currently more than 90% of integrated circuits and semiconductor chips are ultrasonically welded [9]. So far there is no fully understood explanation of this process however it is known that metal is softened by ultrasonic energy. The softened ball sweeps aside the entire brittle oxide surface of the Al through ultrasonic motion, thus cleaning the pad surface as shown in Figure 1. Moreover the ultrasonic motion and the generation of heat due to this motion supplies metal-metal inter-diffusion activation energy. The activation energy also helps to overcome all the remaining barriers that were left during surface cleaning.

Many failures could arise due to ultrasonic wire bond formation. Some reviews of these failures are studied in past [10]. One of well-known failures is first bond (on the integrated circuit bond pad) breaking when second bond is made onto the package.

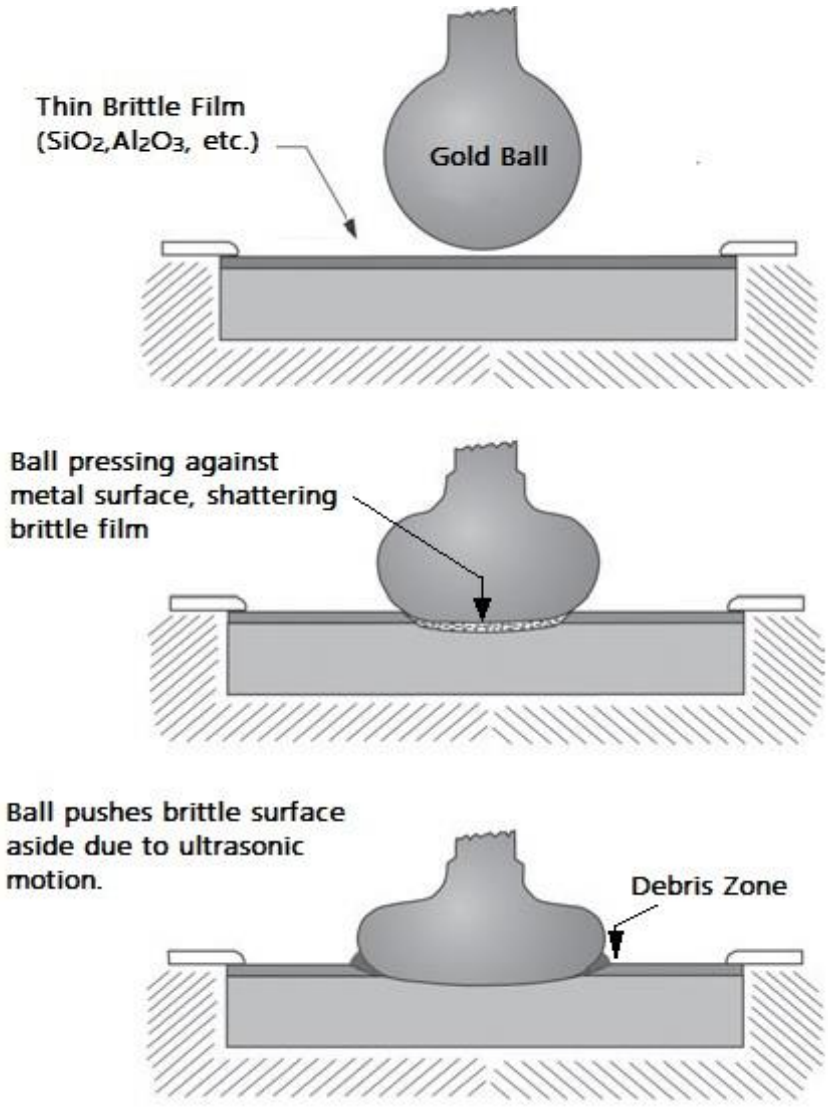

Figure 1 US Energy Cleaning Surface Oxide Film

The big advantage of using ultrasonic bonding is that it requires lower bonding force than thermos-compression bonding, resulting in reduced mechanical stress on the chip and package, which is one of the major requirements in modern technologies due to delicate chips which are susceptible to cracking and deformation.

Through several past studies it is found that ultrasonic frequencies from 60 KHz to 150 KHz give satisfactory results. Also increasing USG from 60 KHz to 90 KHz reduces the bonding time[11-13], bonding temperature [12, 14] and reduces (?) bond strength [15]. These are also proven by another author, adding that there is no statistical significant difference between bonds made at 120KHz and 60KHz, however at 120KHz significant time and cost saving could be achieved with almost no degradation in bond strength [16].

2.2.3. Bonding Force

Bonding force is another principal process variable. The selection of bonding force is very much dependent on other factors including free air ball size, temperature and USG. Depending on other factors a very big ball with relatively small IMC area could be formed as shown in Figure 2. On the other hand, if the bond force is very high it could cause smashing of ball on the aluminum pad, like in Figure 3. This is not desirable due to ineffective increased contact area. The bonding force is selected based on other factors so that a good looking bond ball could be created as shown in Figure 4 which is not smashed and has contact area diameter nearly as large as the ball diameter. (K&S bonder guide)

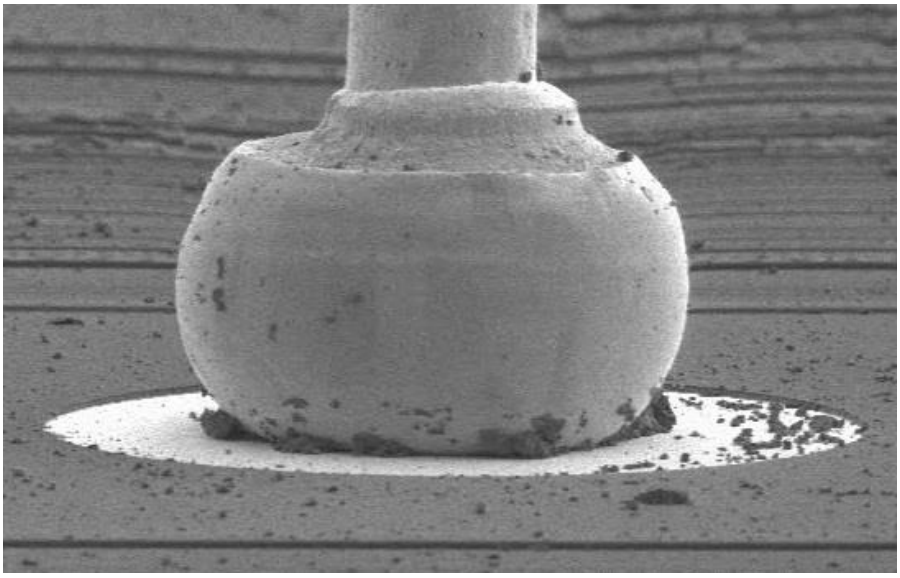

Figure 2 Large Ball Bond with Small Contact Area

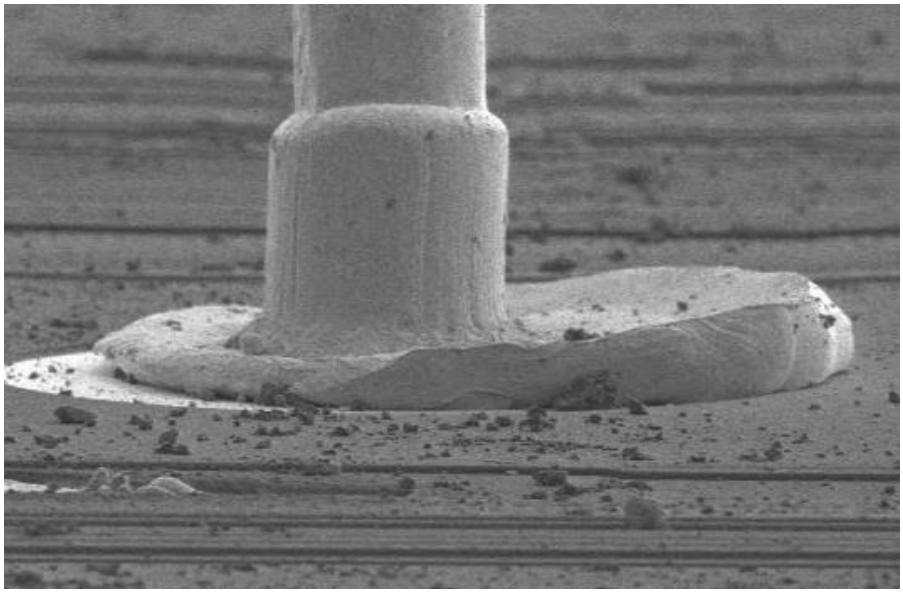

Figure 3 Smashed Ball Bond

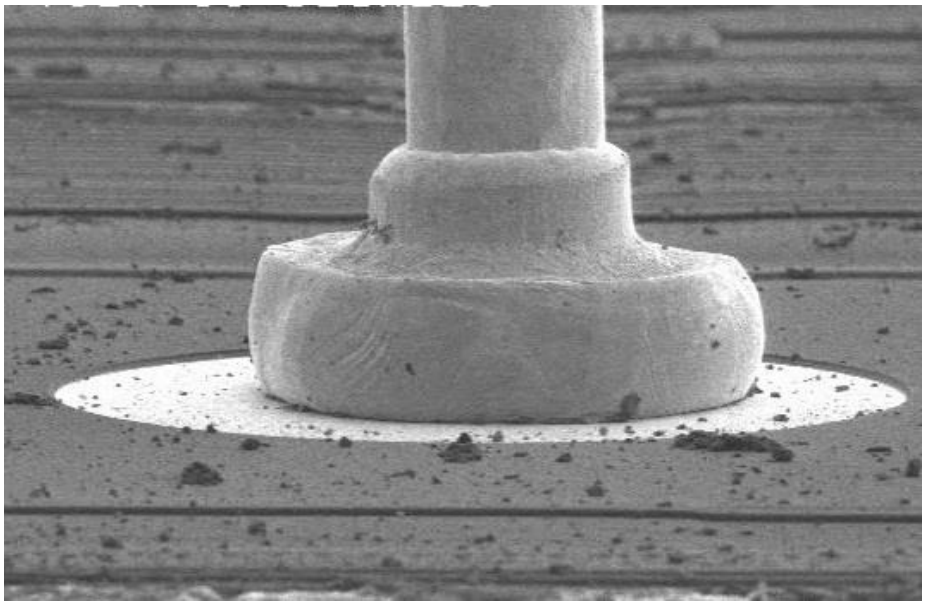

Figure 4 Good Looking Ball Bond

Increase of bonding force gives better ball shear response, but too high bond force causes overstress on bond interface which degrades ball shear results [17].

2.2.4. Free Air Ball (FAB)

In thermos-sonic wire bonding the size of the ball is very important for bond quality and strength. The term “free air ball” refers to the formation of a ball shape at the tip of the bonder due to the high voltage spark which melts the wire tail. Electronic flame-off (EFO) and time are most important factors in FAB formation [18]. There are three distinct steps in FAB formation which are incubating period, melting and solidification [19]. These steps could be seen in Figure 5. The time for each step can be varied depending on the FAB specifications required.

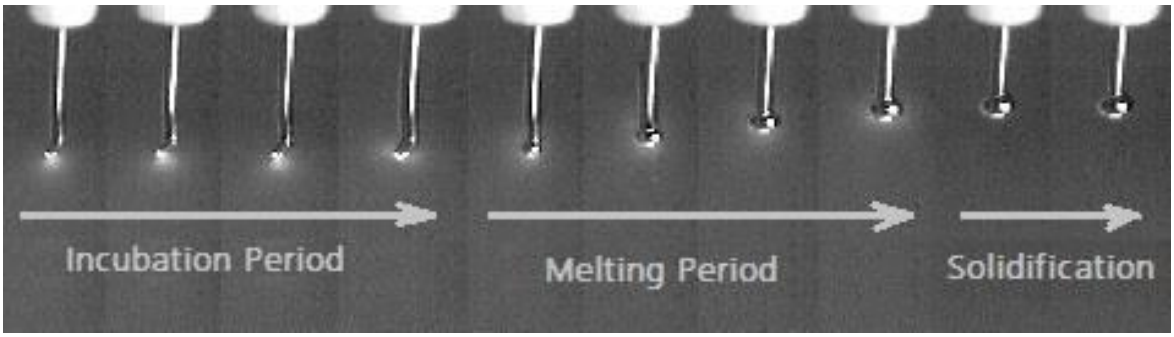

Figure 5 FAB Formation Process [19]

2.2.5. Capillaries

The last, but most important factor under consideration for this experiment is capillary type. Capillaries control the shape and size of the bond and is also source to transfer the ultrasonic energy to the bond [20]. Internal and external shape and dimensions of the capillary give necessary features that form the bond. Drag and friction due to inner shape and material of capillary are very important in controlling flow of the wire and provide tension. Too much friction can break wire and bond, cause deformation of the loop shape and tear or scratch the wire surface. Figure 6 shows cross section of a typical capillary. There is a large range of available capillaries. For current experiment, only high frequency and bottle neck capillaries are considered. The capillaries are manufactured by NDCI/ K&S. Model numbers for the capillaries are as below.

High Frequency: 70 Micron High Frequency Capillary (Model 414SD-2049-R3M)

Bottle Neck: 70 Micron Bottle Neck Capillary (Model 414FD-2049-R35)

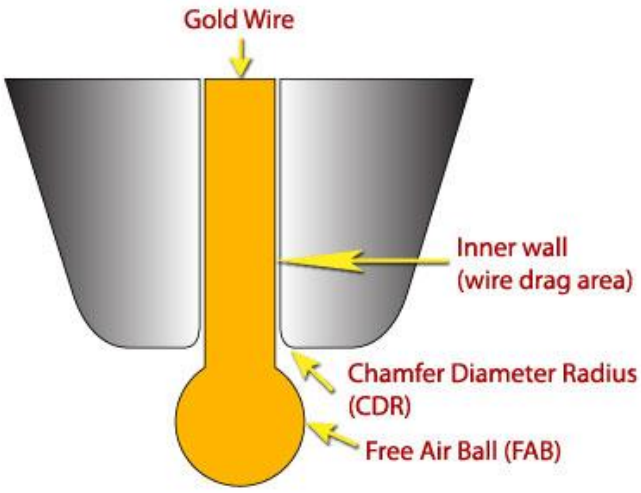

Figure 6 Cross Section of a Capillary

2.3. Ball Bonding Process

The ball bonding is a repetitious process which can be explained in 7 steps as shows in Figure 7. The Au wire is passed through the hollow capillary, the end of the wire coming out of the bottom end, which is melted by the EFO. The melted wire creates a ball like structure which starts to solidify. The capillary descends down and presses the Au ball against the Al bond pad with sufficient bonding force. The inside cone or radius holds the ball during the bond formation. The surface of the bond pad is usually set to some high temperature by setting a staging temperature where the die is placed for bonding. For thermos-sonic Au ball bonds, ultrasonic energy along with high pad temperature causes atomic diffusion between Au wire and the Al bond pad surface, causing formation of IMC. After formation of the first bond the capillary rises with opened wire clamp, releasing enough wire to form a wire loop between first and second bonding surfaces. The capillary repositions over the second bond surface forming a

precise wire loop as the capillary moves with an open clamp. Once a required wire loop is achieved, the capillary descends to the second bonding surface and presses the wire onto the metal surface creating a wedge bond. At this point the capillary clamp closes and capillary rises, which breaks the wire just above the wedge bond. The same length of wire is left out at bottom of the capillary as at the start, to form another Au ball of same size and dimension using EFO, and the bonding process is then repeated [21, 22].

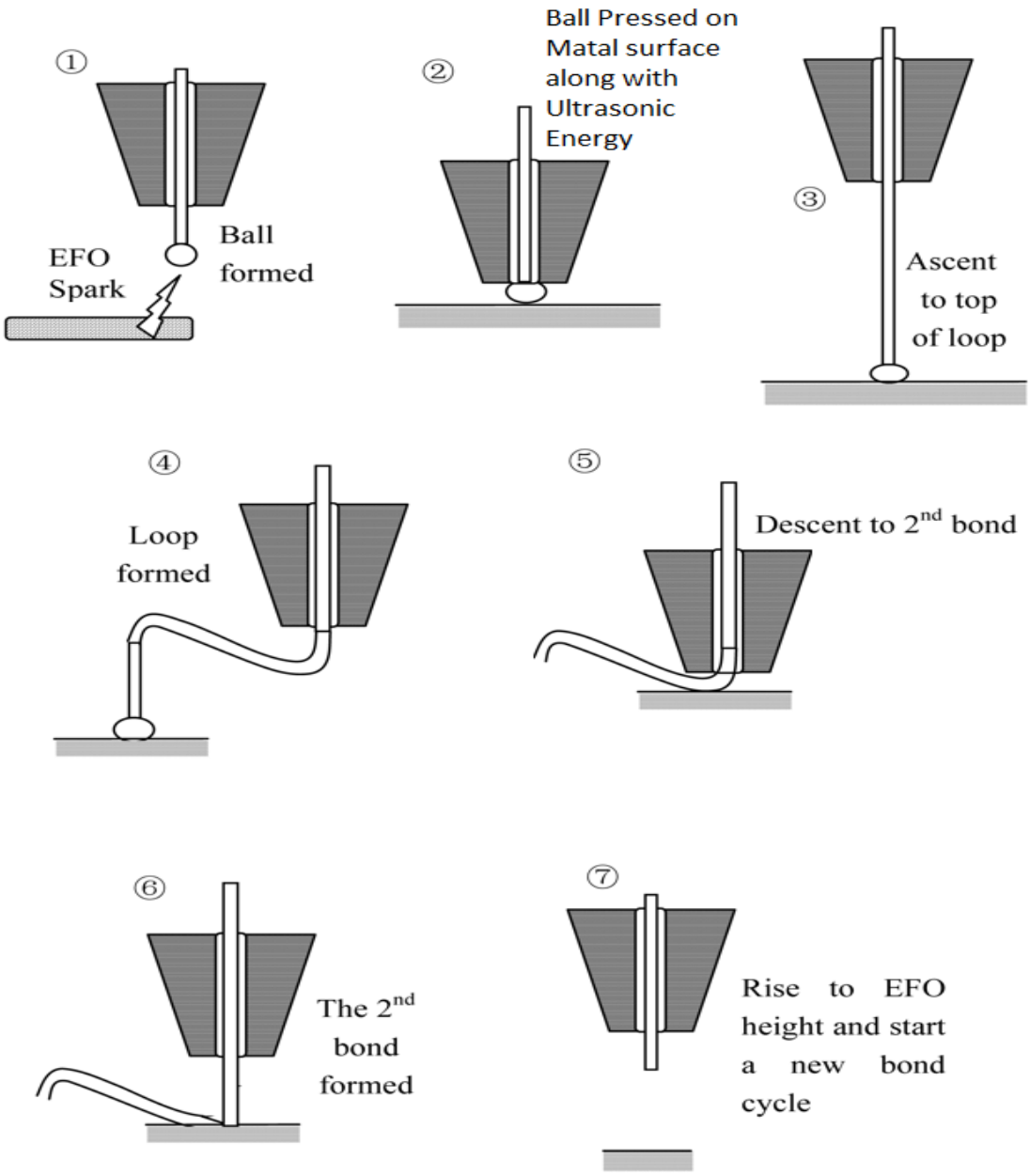

Figure 7 Au Ball Bonding Cycle [23]

Chapter 3

3. Materials and Methods

This chapter covers all the steps required for preparation of ball bonds for the experiment and the testing and measurement methods used to measure the ball bonds strength, shape, contact area and failure analysis. The first part of the chapter will discuss the ball bond preparation steps.

3.1.Bond Preparation

3.1.1. Wafer Sawing

The first and most important process for die preparation is wafer sawing. During the sawing process wafers are placed on sticky dicing tape which holds the dies, dicing tapes are selected depending on the size of die and thickness of the wafer. Wafer is placed on a metal frame which keeps the wafer in its place during sawing for high precision. The saw runs through the subscribed lines which are programmed in the machine to cut the die according to die size requirements. Once the wafer is sawed it is left on the dicing tape for the next step for die extraction.

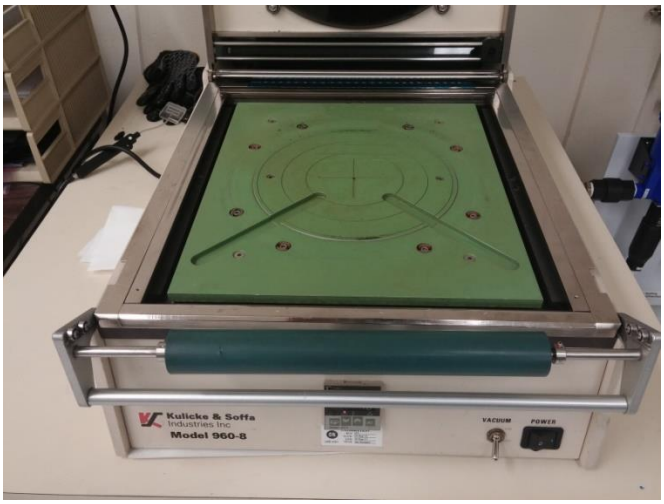

Figure 8 Wafer film mounting machine

3.1.2. Wafer Stretching & Die Extraction

Following the wafer saw process is tape stretching. The wafer dicing tape is stretched using a wafer expander for equal and balanced stretching of tape from all parts of the wafer, separating the dies from each other for easy extraction. Next each die is extracted from the tape by using a machine as shown in Figure 9. This machine has a small needle-like structure which is placed right below the die and then pushed up. The needle punches the die off the dicing tape, and the die is then handled by using a suction machine, placing the die into die tray.

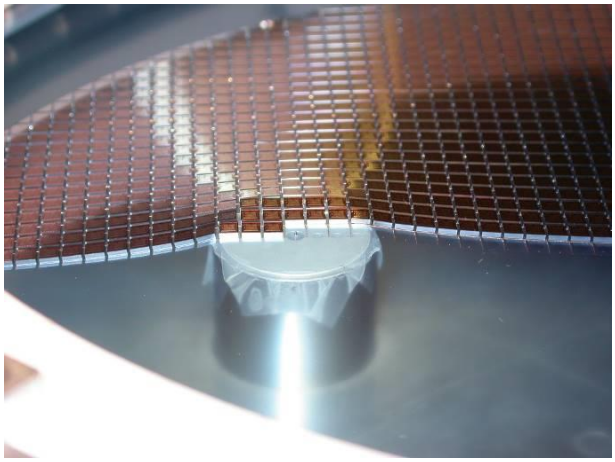

Figure 9 Die Extractor

3.1.3. Die Attach

Once the die are extracted from the dicing tape, they are now ready to be attached on the package. Dual in-line ceramic packages with 16 pins are used for this set of experiments. The package is shown in Figure 10. They were available as leftovers at the production facility, donated to this project.

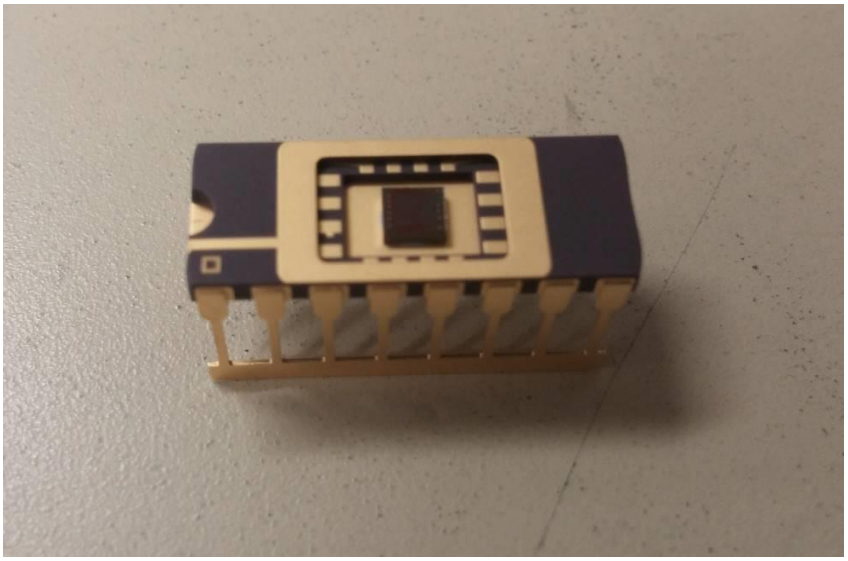

Figure 10 16 Pin Dual-in-line Ceramic Package

A small dot of epoxy die attach is placed on the package followed by placing die on the package, the package is evenly pressed and gently rubbed for equal distribution of the epoxy between the die and package for strong and reliable attachment. Epoxy is the most commonly used die attach because of its cost-effective solution. Figure 11 shows the manual die attaching process being done by the author.

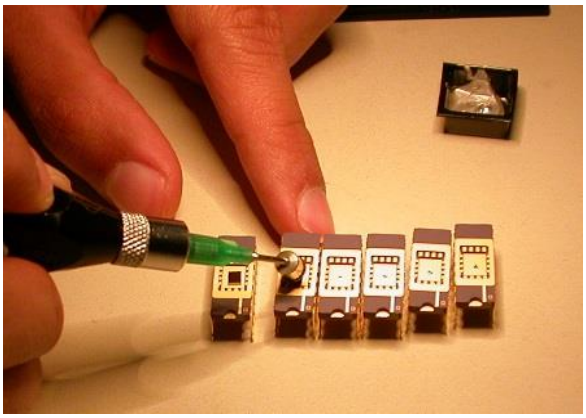

Figure 11 Die Attach Process using Epoxy

3.1.4. Baking

Once the die are attached on the packages, the next step is baking, to strengthen the epoxy to hold the die in its position and remove any moisture from the package. Figure 12 shows the attached die in the baking oven.

Figure 12 Package Baking Machine

3.1.5. Bonding

The final step is the thermos-sonic ball bonding. The bonder is programmed for each treatment by inputting the values for each factor that in the bonding recipe. Once the recipe has been setup along with required capillary and threaded Au wire, the package is placed on the bonding stage. Each package is placed on the bonder for at least 30 seconds prior to bonding so the ceramic package will stabilize at the desired temperature. Figure 13 shows wire bonder with bottleneck capillary mounted.

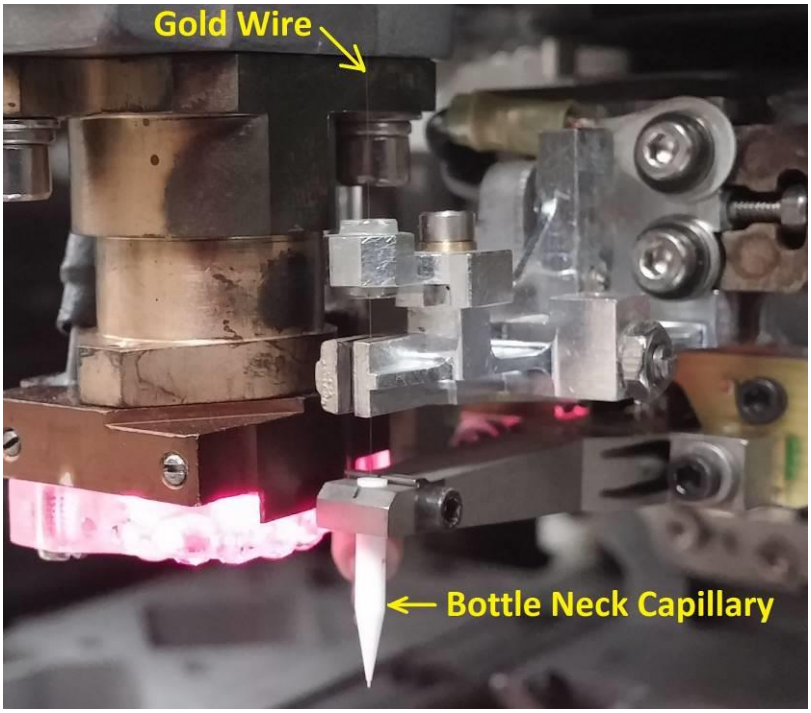

Figure 13 Wire Bonder with Bottle Neck Capillary Mounted

Bonder settings are saved in a file so that each time a new experiment is performed all factors are restored to same value, and only the varying factors are changed. The factors that were kept constant throughout all experiments are listed in Table 1.

Table 1: Constant Factors and Values

Factors	**Values**
Bonding time	12ms
Wire dia	1 mil
Tip	20 mil
EFO current	30 mA
FS Threshold	10 grams
CV	.30 mils/ms
Kink Height	7.5 mils
reverse motion	7 mils
loop factor	4.5
SFI	25 degree
Span Length	40%

3.2. Measurement Methods and Failure Analysis

In the semiconductor industry, the most widely used measurements for ball bond strength and reliability are Bond Pull testing and Ball Shear testing, SEM Cross section study and Optical Microscope analysis.

3.2.1. Pull Testing

The most common type of bond test used to measure bond quality is the wire pull test. For wire pull test, the wire is pulled up vertically by a hook until there is a failure. The hook should be placed at same position of the wire each time to get consistent pull strength results, as changing the location changes the strength of pull test due to change in distribution of pull strength on two bonds with the change in pull location. Figure 14 shows a micrograph of the hook beneath the wire loop, preparing for a bond pull test. The ball bond to be tested is on top of the attached die in the upper right.

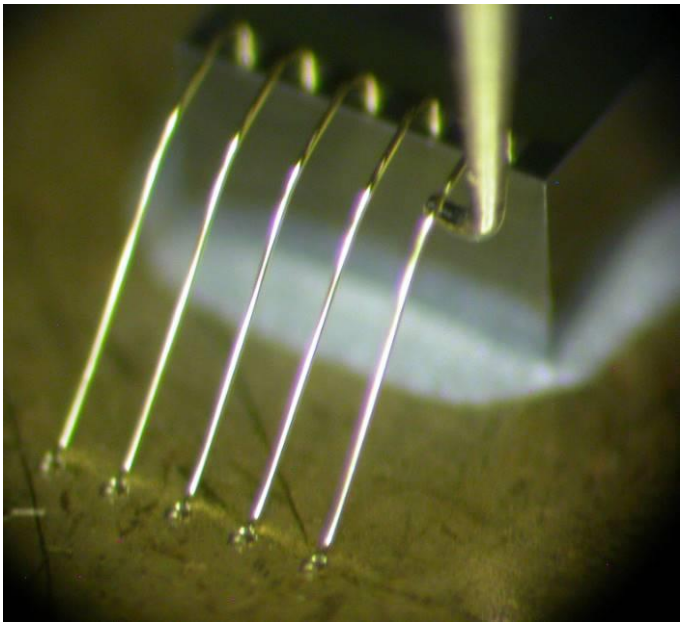

Figure 14 Ball Pull Test

If a ball lift or weld lift occurs, the bond quality is unacceptable even if it occurs at very high pull value. Different types of pull test failures are described below and also in Figure 15.

Ball Lift Failure:

Ball lift failure indicates that the ball to metal surface interface is weak or contact is not properly made due to contamination. A ball lift could also be due to poor bonder set-up, poor parameter settings or worn out tools.

Ball Neck Failure:

Failure of the wire just above the ball is a ball neck failure. This is one of the most common failure modes. Neck break is due to fracture in the neck, which is the area where the wire meets the ball bond. Incorrect bonding recipe can cause a thin, weak or cracked neck.

Wire Break at Mid Span:

Wire break at mid span is the most desired type of failure. Here the wire breaks at the mid span and gives the highest pull strength value, near the ultimate tensile strength of the wire.

Heel Break:

Heel break is due to breaking of the wire at its wedge bond due to a fracture in the heel at the second bond, which is on the package. The major cause of the heel break is a micro crack at the heel. The cause of heel micro cracking is the bonding parameters such as very high bonding force, high ultrasonic energy, or incorrect wire looping parameters.

Weld Lift:

Weld lift is similar to ball lift but is detachment of the wedge bond from the package. Weld lift is due to improper bonding recipe, and like ball lift is not acceptable. Weld lift could be caused due to hard metallization, contamination of bond pad, improper clamping or improper coupling between lead frame and capillary.

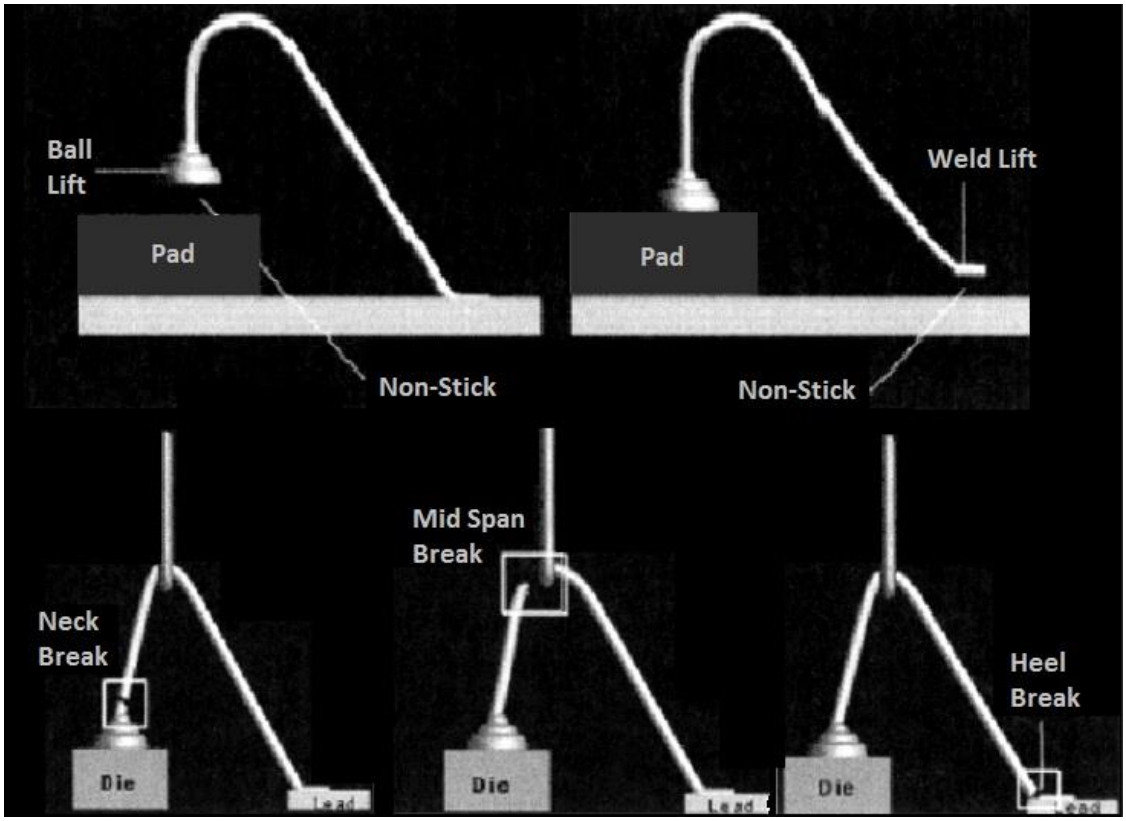

Figure 15 Ball Pull Failures [23]

3.2.2. Shear Testing

To measure strength to break the ball to pad interface, shear testing is required. Shear testing is the most important test to assess the characteristics of a ball bond. Shear testing reveals the weakest point of the ball bond, which is often the part of the Au ball right above the ball bond IMC. A ball bond can withstand up to eight times the wire pull strength. Figure 16 is a micrograph of the shear tool in place to do a ball shear test, where the blade will move towards the viewer.

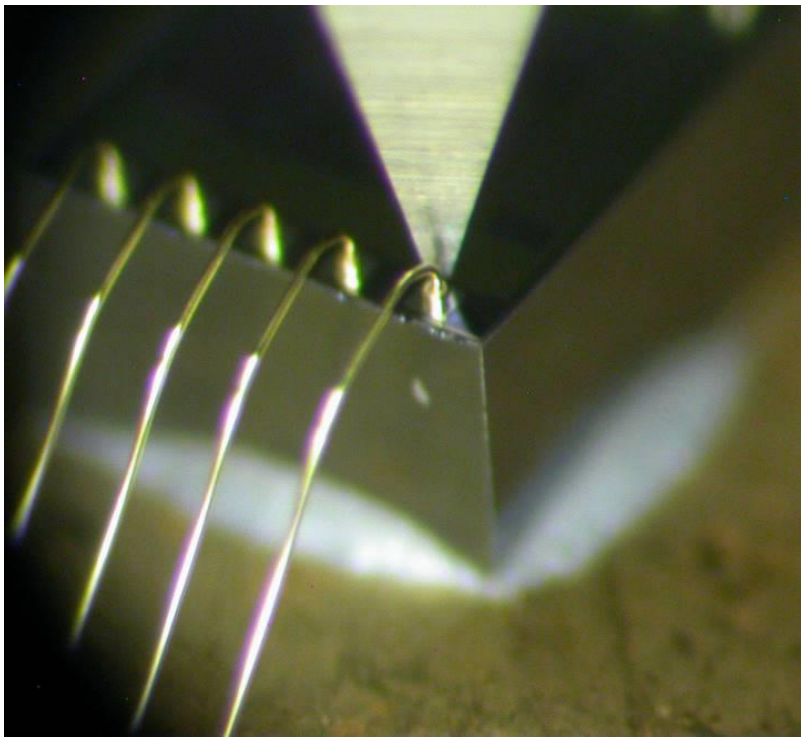

Figure 16 Ball Shear Test

The shear tool is placed adjacent to the ball bond. The blade then lifts a little above the surface of the bond pad to avoid any scratching, then moves horizontally, parallel to pad surface, until it pushes the ball off the bond pad. The shear test is illustrated in Figure 17.

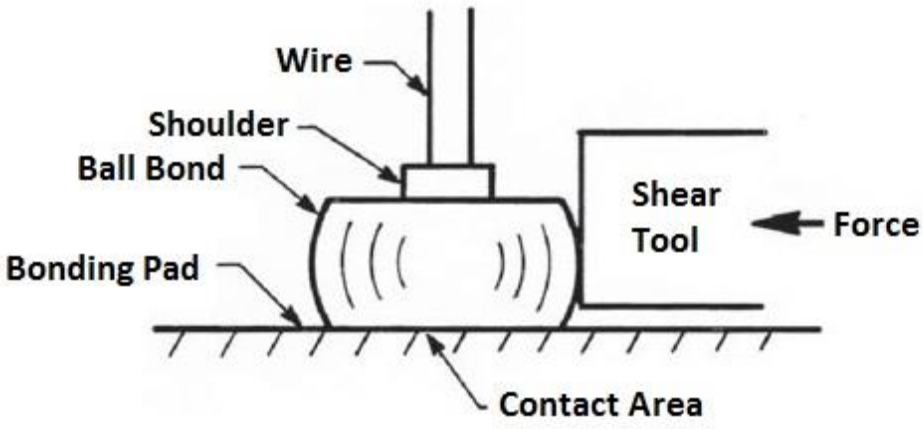

Figure 17 Shearing Process

The failure analysis of shear test tells a lot about the bond and the IMC. Failures modes can only be determined by a trained operator using high power microscope inspect. Types of shear test failures are shown in Figure 18 and explained below.

Ball Lift:

Ball lift is a type of failure where almost no Au is left on the bond pad, with little visible effect on the bond pad or die. This type of failure is mostly due to very poor and low IMC formation. In such cases the Au ball bond was not strongly bonded to bond pad.

Pad Lift:

Pad lift failure is when bond pad comes off from the die as a result of the shear test. In this type of failure, the Al pad was not properly attached to the underlying surface, and it comes off exposing the surface underneath it. A thermo-sonic bonding

recipe with too high an energy can ruin the adhesion in the bond pad layers to cause this failure.

Ball Shear:

When a Au layer is left after shearing due to good and strong intermetallic formation it is known as ball shear and is the desired outcome for the shear test. A ball shear shows good strength of the IMC and the pad and its underlying structure.

Cratering:

Cratering is the term used when the ball bond lifts along with some part of bond pad and underneath layer due to mechanical damage. Cratering occurs due to cracks generated under the bond pad during bonding, which would be an indication of too high an energy used in thermos-sonic bonding.

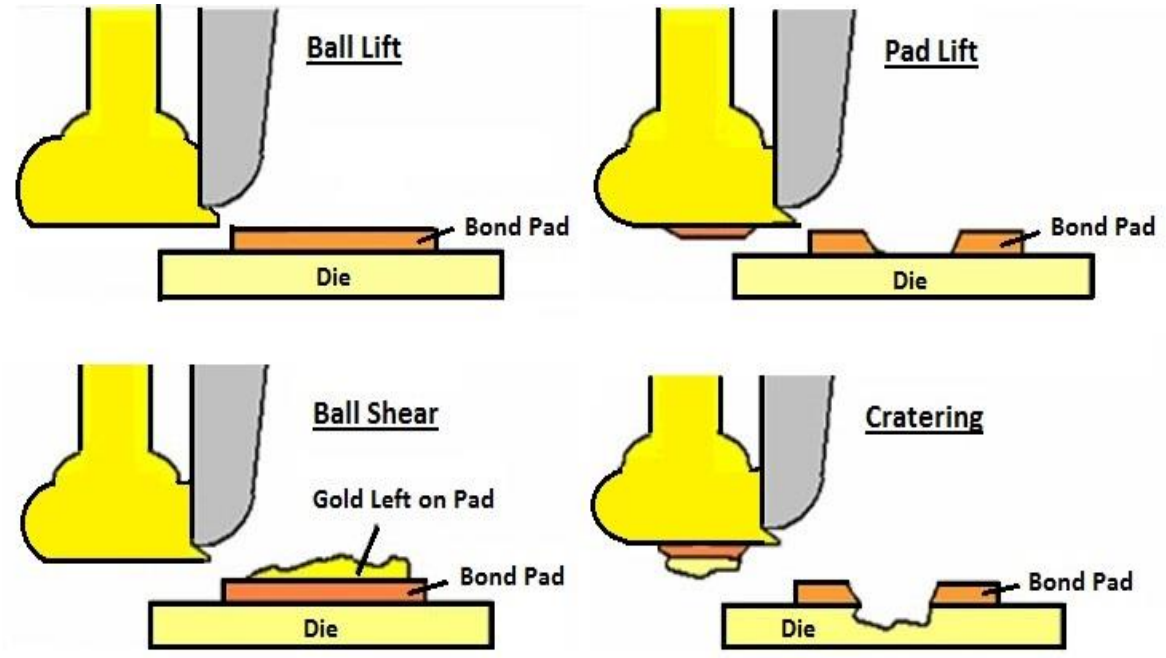

Figure 18 Shear Test Failures

3.2.3. Scanning Electron Microscope (SEM) Analysis

Scanning electron microscope pictures of ball bonds are used for analysis. It is one of the best ways to visually inspect the bonds and identify failures such as poorly shaped ball bonds. In SEM, a focused beam of electrons is used to scan an object, and the electrons produce signals which are then detected. The electrons carry information about surface topography and materials composition.

The SEM is used to study the profile or lateral cross section of ball bonds. Accurate measurements of ball diameter, ball height and ball contact diameter are only possible by using the SEM. Figure 19 shows an example SEM.

Figure 19 Scanning Electron Microscope

3.2.4. Optical Microscope Analysis

Another important ball bond analysis method is visual inspection by Optical Microscope. The optical microscope shown in Figure 20 uses visible light. Under Optical Microscope view, bond pads and ball bonds are inspected to identify failure modes caused during pull and shear test.

Figure 20 Optical Microscope

Chapter 4

4. Design of Experiment

This chapter explains the steps involved in planning experiments for the project.

4.1. Overview of Experiment Planning

The first step for process optimization is to identify all possible factors that can affect the quality and reliability of the product. The list of the factors could be very long, including dozens of factors controlling the outcome of a process, so the value of a each factor should be recorded. Most factors should be fixed, with only limited number of varying factors to be considered as be major controlling factors.

The most commonly used approach is one factor at a time (OFAT) but that requires a large number of experiments and doesn't provide enough information about interactions of factors. Another approach is factorial design. For an environment where experiments are costly and time consuming a two level factorial design is more efficient and can efficiently reveal critical interactions. By limiting the tests to only two levels the total numbers of experiments are minimized. At the beginning of investigation of many factors must be considered, but approaching the optimum point, the number of factors can be reduced by identifying key driving factors for the process.

4.2. Strategy

Basics of planning a two-level factorial design are well documented [24, 25]. Factorial designs consist of series of experiments in which all multiple factors are varied simultaneously instead of one at a time. Two-phase experiment strategy is used for following experiment, the two phases are.

Phase 1: Use of two-level factorial design for screening to separate major factors from other factors. Phase 1 will help us make some conclusion about the factors and interactions between them, also to identify the places for optimization and which levels are not worth to investigate.

Phase 2: Phase two of the experiments involves in-depth investigation of surviving factors and move the process to optimum location. Based on phase 1 results a recommendation of phase 2 experiments is also made.

4.3. Fractional Factorial Design

For screening of factors a fractional factorial design will do the job, to run full factorial for all high and low level is not required. Five factor fractional factorial experiments can be symbolically expressed as 2^{5-1}. The symbol explains that there would be total of 16 treatments and not 32. Table 2 shows the data for partial factorial design in the first experiment. The selection of 5^{th} factor that is capillary type is based on the signs multiplication of signs in each interaction column. The following table shows partial factorial design for first experiment. There are 2 additional treatments added to 16

designed experiments, these treatments are performed throughout the experiments to check consistency of the experiment.

The author mistakenly mixed the two different capillaries in this design, causing insufficient outcomes after the initial experiment, so additional screening experiment treatments were run as will be shown later.

Table 2 Partial Factorial Design for First Experiment

Treatments	Temperature	Force	USG (current settings)	FAB	Capillary
1	+	+	+	+	+
2	+	+	+	-	-
3	+	+	-	+	-
4	+	+	-	-	+
5	+	-	+	+	-
6	+	-	+	-	+
7	+	-	-	+	+
8	+	-	-	-	-
9	-	+	+	+	-
10	-	+	+	-	+
11	-	+	-	+	+
12	-	+	-	-	-
13	-	-	+	+	+
14	-	-	+	-	-
15	-	-	-	+	-
16	-	-	-	-	+
17	-	0	0	0	+
18	-	0	0	0	-

4.4. Factors and Respective Values

4.4.1. Major Factors under Observation

All the factors and their respective values for each level are given in table 3, the reasons for selecting these values are already described in previous chapters; a wide

range with large difference between levels is selected in order to reach the optimum point quickly. Later experiments examine more levels, with smaller differences resulting in the outcomes.

Table 3 Factors and Level Values for First Experiment

Factor	Low Level (-)	High Level (+)	Mid-level (0)
Temp	180	200	190
force	15	30	22.5
USG	85	105	95
FAB	2	2.4	2.2
Capillary	BN	HF	

4.4.2. Non varying Factors

Other non-varying factors that are of great importance but will be kept constant throughout the experiment are given in Table 4 along with the each value. The values for these factors will be important for future work if extending experiments are required.

Table 4 Non-Varying Factors with Values

Non-varying Factors	Values
Bonding time	12ms
Wire diameter	1 mil
Tip	20 mil
EFO current	30 mA
FS Threshold	10 grams
CV	.30 mils/ms
Kink Height	7.5 mils
reverse motion	7 mils
loop factor	4.5
SFI	25 degree
Span Length	40%
Second Bond	
USG	95
time	55
force	65

4.4.3. Finalized Experiment Design

In order to finalize the design each symbol is replaced with the respective value of the factor level, and all the treatments are randomized. Table 5 shows final design of first experiment along with the values. Note that treatment 17 and 18 are placed in between at mid points and at the start and end of each session to check consistency of experiment, so in case if there is an accidental change in some factor which could cause unwanted shift in results the treatment 17 and 18 will identify it.

Table 5 Design of Experiment for 1st Experiment

Treatments	Temperature	Force	USG (current settings)	FAB	Capillary	Repetetion (Number of dies getting treatment)
18	180	22.5	95	2.2	BN	6
12	180	30	85	2	BN	6
15	180	15	85	2.4	BN	6
14	180	15	105	2	BN	6
9	180	30	105	2.4	BN	6
18	180	22.5	95	2.2	BN	2
8	200	15	85	2	BN	6
5	200	15	105	2.4	BN	6
2	200	30	105	2	BN	6
3	200	30	85	2.4	BN	6
18	180	22.5	95	2.2	BN	2
17	180	22.5	95	2.2	HF	6
16	180	15	85	2	HF	6
11	180	30	85	2.4	HF	6
13	180	15	105	2.4	HF	6
10	180	30	105	2	HF	6
17	180	22.5	95	2.2	HF	2
7	200	15	85	2.4	HF	6
6	200	15	105	2	HF	6
4	200	30	85	2	HF	6
1	200	30	105	2.4	HF	6
17	180	22.5	95	2.2	HF	2
					Total Die	116

Chapter 5

5. Experiments & Results

5.1. First Experiment

The initial experiment consisted of 18 treatments. A sample size of 6 die was chosen for each treatment. Each die had 11 bond pads, so in total each treatment had 66 samples of ball bonds. After design of experiment for first experiment was finalized it was followed by the actual bonding process. The steps involved in sawing, extracting dies from the wafer, die attach and baking were explained in previous chapters.

The bonding process took place at one of the Semiconductor industry prototype assembly area. The die were ball bonded with 25µm Au wire using a K&S IConn Bonder as shown in Figure 21. Each package was bonded according to the planned treatment and order. All non-stick on pad readings were recorded during the bonding process. Also the time each package spent on the staging unit was controlled to 30-40 sec before they were bonded.

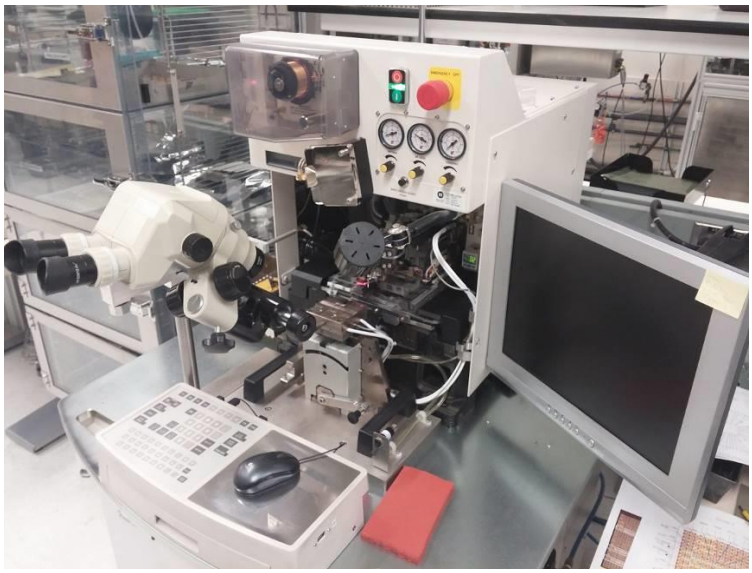

Figure 21 K&S IConn Bonder

All the packages were numbered according to treatment number and package number, e.g. the 3rd package for 2nd treatment was named as 2C, where 2 represents treatment number and the alphabetic character represents the sequential package number for that particular treatment. Later all packages were placed in anti-static package tubes to protect them from any kind of damage or contamination during transportation and storage.

Following the bonding process was pull test. If the strength of the ball bond is less than that of the ball neck and wire then a ball pull off is observed, as an undesirable failure mode. All ball bonds were pull tested f using the Royce System 580 machine, using the Royce Instruments wire pull module (TMW – 100G - 12798) shown in Figure 22.

Figure 22 Royce Instruments Wire Pull Module

Once the pull test is performed on the entire ball bonds, the surviving ball bonds go through the ball shear test while the ball bonds that had “ball pull off” go to optical microscope observation for analysis of bond pads and IMC. The shear testing is fundamental test to show ball bond strength, although the results from shear testing are the not final judgment, as some of the balls might show high shear strength but they could have weak ball neck or a smashed ball shape.

Of the 6 die in each treatment, one die was sent for SEM photographs to analyze shape and physical characteristics of the ball bonds. These SEM photos were also used to measure ball diameter, ball contact diameter, ball contact area approximation and ball height.

After analyzing the results from 18 treatments, an extended group of experiment was performed to fill in some of the important missing treatments from the partial factorial design. These treatments are named Treatment 19 to Treatment 26. The design of this extended experiment is given Table 6.

Table 6 Extended Design of Experiment - 1st Experiment

Treatment No.	Temp	Bonding Force	USG	FAB	Capillary
19	200	30	105	2.4	BN
20	200	30	105	2	HF
21	200	30	85	2.4	HF
22	200	30	85	2	BN
23	180	30	105	2.4	HF
24	180	30	105	2	BN
25	180	30	85	2.4	BN
26	180	30	85	2	HF

5.2. Results

5.2.1. Pull Test Results

The first bonding experiment showed no NSOP for any of the treatments, but some ball pull offs were observed during bond pull test. There were 10 ball pull offs for treatment 7 and 19 ball pull offs for treatment 13. More than 2-3 ball pull offs may be acceptable because of chances of pad contamination or some other errors while bonding in this lab experiment, but the number of ball pull offs found in treatment 7 and 13 are enough to mark these as unwanted treatments. The rest of the treatments showed no ball pull off, which is mark of good bonding, showing that the designed experiments are mostly inside an acceptable range. Table 7 shows summary of these bond pull tests.

Table 7 Experiment 1 - Pull Test Results

Treatment No.	Pull Froce (mean)	Ball Pull Off
1	11.46	0
2	11.66	0
3	11.40	0
4	11.94	0
5	11.77	0
6	12.14	0
7	11.54	10
8	11.98	0
9	10.56	0
10	10.91	0
11	10.50	0
12	10.88	0
13	10.68	19
14	11.30	0
15	11.27	0
16	11.21	0
17	10.21	0
18	10.52	0
19	11.42	0
20	11.87	0
21	11.58	0
22	11.20	0
23	10.63	0
24	11.04	0
25	11.04	0
26	11.38	0

The following graph show the box plot of Pull Force vs Treatment number, indicating the distribution of pull force for each treatment, with black dots representing outliers. Red marked treatments are the ones which had ball pull offs. The graph in Figure 23 shows that pull values for all the ball pulls are in acceptable range (which is

above 8gf for this Au wire diameter), so all the treatments are good enough for further studies and experiments, except treatment 7 & 13.

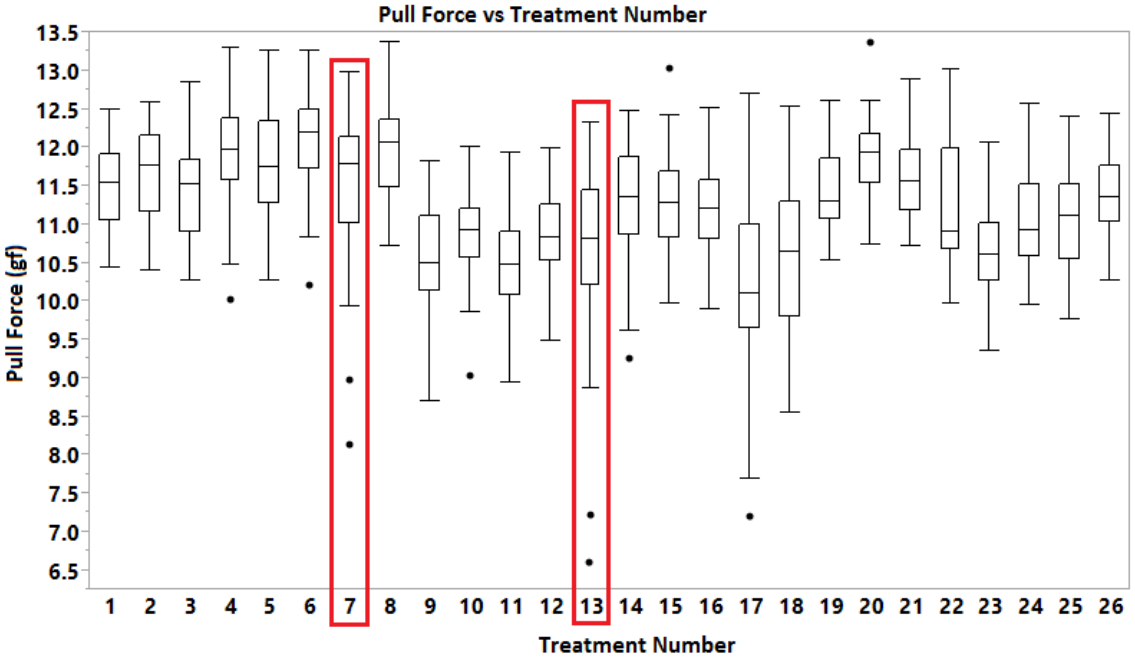

Figure 23 Experiment 1 - Pull Force vs Treatment Box Graph

5.2.2. Shear Test Results

The first experiment shear test results showed no failures, all ball sheared in a good way with no signs of ball lift, pad lift or cratering. The graph in Figure 24 shows shear values of all the treatments. Some of the treatments had very small shear force values while some showed good values. Three of the treatments were having good shear values but still were considered as failures because this treatment had smashed ball bond. Smashed ball bonds have small ball height so they might cover more of pad surface but due to small ball height they are more vulnerable to neck break and cracks in the

structure beneath bond pad Al. Treatment 4, 10 and 20 are marked red in the graph showing treatments with smashed balls.

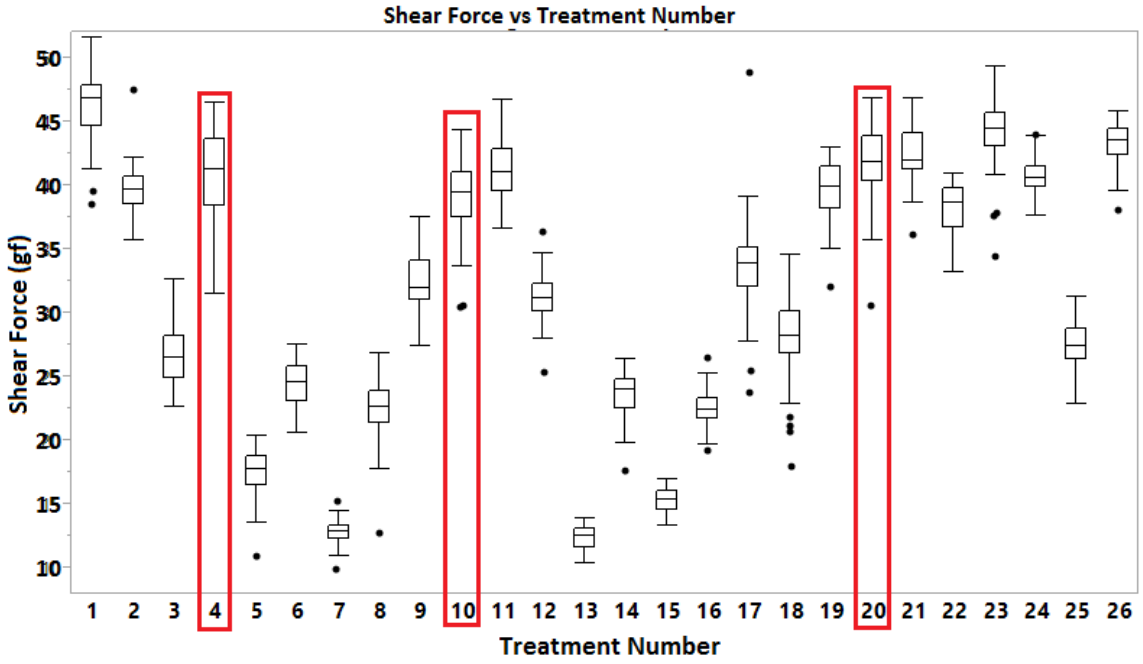

Figure 24 Experiment 1 - Shear Force vs Treatment Box Graph

5.3.Second Design of Experiment

Based on results from first experiment a second experiment is planned, the purpose of second experiment was to find the optimum recipe that could give better results than those obtained through recipes in first experiment.

The following table 8 shows treatments arranged by shear force mean values with best treatments on the top for high frequency capillary and table 9 for bottle neck capillary. Treatments with failures are marked red. The ball diameter is intended to remain at or near the targeted ball diameter, so for a ball pad of 75µm width, the average ball diameter should be a maximum of about 70µm, leaving at least 2.5µm of spacing

between ball and pad borders for bond misalignment tolerance. The experiment goal is to achieve an optimum recipe for about 70µm diameter and also for smaller ball diameters for bond pads down to 50µm.

Table 8 Experiment 1 HF Capillary Results - Arranged by High Shear Force First

Treatment	Shear Force	Ball Dia	Temp	Bond Force	USG	FAB
1	46.36	78.77	200	30	105	2.4
23	44.10	74.52	180	30	105	2.4
26	43.13	68.01	180	30	85	2
21	42.24	71.76	200	30	85	2.4
20	41.61	80.85	200	30	105	2
11	41.17	76.10	180	30	85	2.4
4	40.66	83.78	200	30	85	2
10	39.11	91.87	180	30	105	2
17	33.65	67.53	180	22.5	95	2.2
6	24.40	59.10	200	15	105	2
16	22.47	55.88	180	15	85	2
7	12.87	63.42	200	15	85	2.4
13	12.38	64.10	180	15	105	2.4

Table 9 Experiment 1 BN Capillary Results - Arranged by High Shear Force First

Treatment	Shear Force	Ball Dia	Temp	Bond Force	USG	FAB
24	40.69	65.68	180	30	105	2
19	39.52	70.06	200	30	105	2.4
2	39.43	63.76	200	30	105	2
22	38.13	59.64	200	30	85	2
9	32.38	71.23	180	30	105	2.4
12	31.29	62.11	180	30	85	2
18	28.20	63.07	180	22.5	95	2.2
25	27.58	69.25	180	30	85	2.4
3	26.59	69.11	200	30	85	2.4
14	23.71	56.97	180	15	105	2
8	22.34	55.19	200	15	85	2
5	17.59	65.40	200	15	105	2.4
15	15.31	63.41	180	15	85	2.4

From analysis of the values in the table it can be seen that all the treatments with bonding force 15g stood last showing poor shear test results although acceptable but not optimum, so for next experiments 15g force for bonding recipe should be avoided. All of the first experiment showed good results other than the ones with 15 g.

For optimization based on current results recipe for BN and HF each for 70µm Bond pad and 60um Bond pad is required, excluding all the recipes with failures and larger than required ball diameter, so further experiments centered around Treatment 24 for ball diameter less than 65um with the BN capillary, and Treatment 6 for ball diameter less than 65µm with HF capillary, Treatment 8for ball diameter near 55µm and Bottle Neck Capillary and lastly Treatment 16 for ball diameter around 55µm and High Frequency Capillary are designed.

Table 10 shows the Design of Experiment for the second set of experiments. All the treatments were randomized, with treatment 17 and 18 placed in between.

Treatments for Optimization of Treatment 24: Treatment number 27 to treatment 30 are treatments with slight variations in temperature and USG setting to try and achieve improved results over treatment 2.

Treatments for Optimization of Treatment 6: Treatment number 31 to treatment 34 are designed to improve results over treatment 6, with slight variations in Temp, Bond Force and USG values.

Treatments for Optimization of Treatment 8 and 16: Treatment 35 to treatment 42 are designed to improve the recipe around treatments 8 and 16, with slight variations in Bond Force, USG and FAB values.

Table 10 Design of Experiment for 2nd Experiment

Treatments	Temp	Force	USG (current settings)	FAB	Capillary	Repetition (Number of Dies)
27	180	30	120	2	BN	4
28	200	30	120	2	BN	4
29	220	30	105	2	BN	4
30	220	30	85	2	BN	4
31	180	22.5	85	2	HF	4
32	180	22.5	105	2	HF	4
33	200	22.5	85	2	HF	4
34	200	22.5	105	2	HF	4
35	180	12.5	85	1.8	HF	4
36	180	12.5	85	1.8	BN	4
37	200	12.5	85	1.8	HF	4
38	200	12.5	85	1.8	BN	4
39	180	15	85	1.8	HF	4
40	180	15	85	1.8	BN	4
41	200	15	85	1.8	HF	4
42	200	15	85	1.8	BN	4
						64

5.4. Second Experiment

The second set of experiment consist of 16 new treatments and 2 existing center point treatments.. Each new treatment was performed on 4 dies and each die has 11 bond pads, for a total of 44 bonds per treatment. The same package type and die from the same wafer were used. Bonding was done using the same bonding machine and operator,

keeping all other factors at the same values as in the first experiment. Pull testing and shear testing was done using same Royce System 580 machine, shown in Figure 25.

Figure 25 Royce System 580 Machine

5.5.Results

The second experiment showed very few failures as this experiment were expected to already be within an optimum range. There were no NSOP, no pull test failures and no smashed balls.

The graph in Figure 26 is a box plot of bond pull force vs treatment number. All treatments have good bond strength and showed no signs of failures or weak pull

strength. Red marked treatments are from bottleneck (BN) capillary while red marked treatments are from high frequency (HF) capillary.

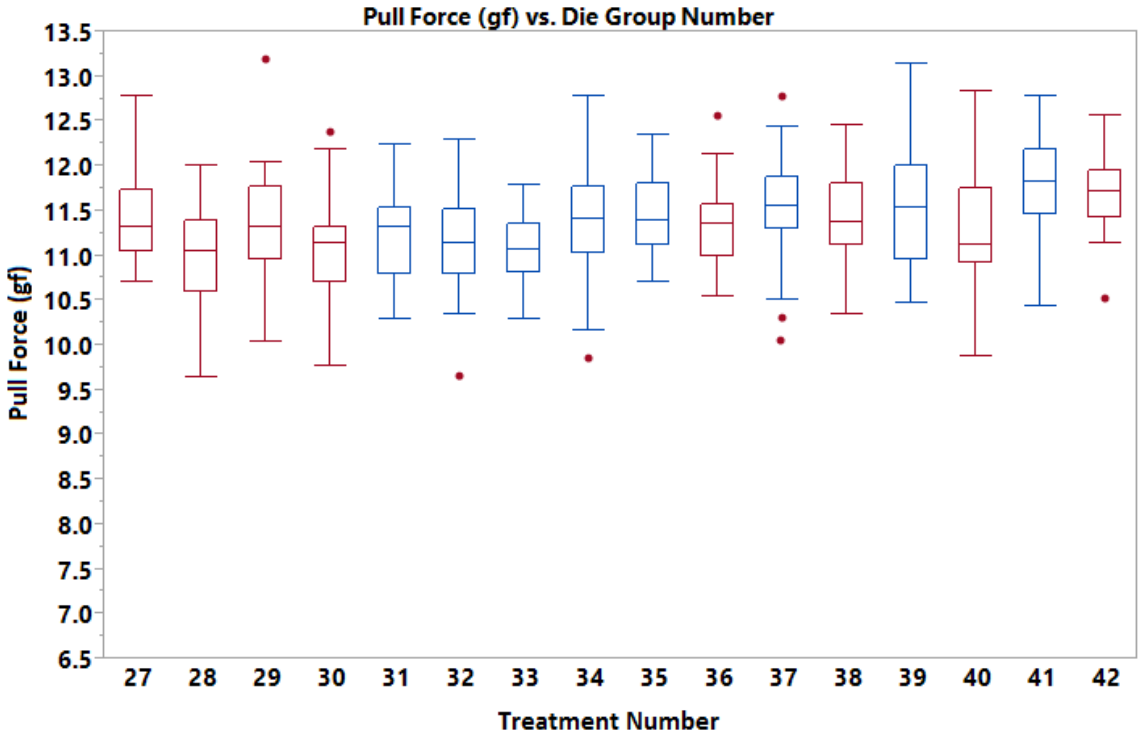

Figure 26 Experiment 2 - Pull Force vs Treatment Box Graph

Next comes the shear test results, treatment 35 to 42. Figure 27 shows lower shear force values due to their small contact area, as these treatments were designed to produce small diameter ball bonds for smaller bond pads. Red marked treatments represents bottleneck capillary and blue represents high frequency capillary being used. There were no cratering, ball lift or pad lift failures observed in shear testing. Further analysis about bond strength and which bonds are best will be discussed in next chapter.

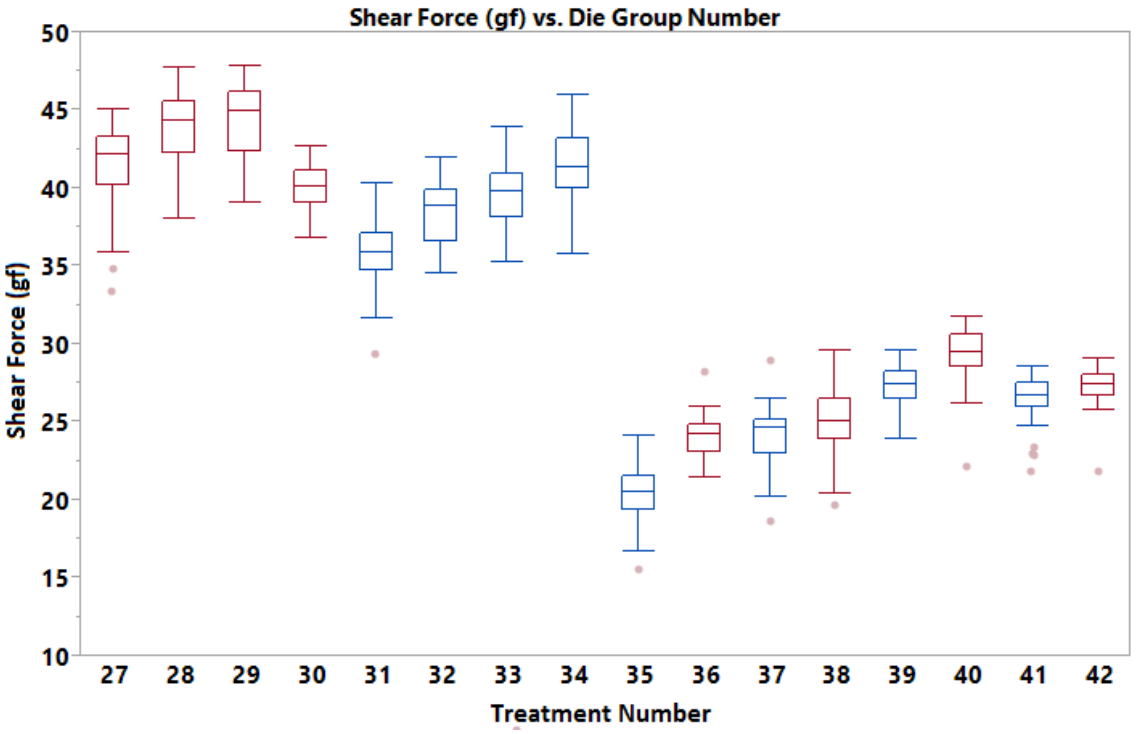

Figure 27 Experiment 2 - Shear Force vs Treatment Box Graph

5.6. Third Experiment

The first two experiments resulted in Au balls with diameters ranging from 50µm to 80µm, but there was a need to investigate bonding recipes with ball diameter as low as 45µm, and their optimization, as well. A third experiment targeted recipes that could possibly produce ball bonds with diameter around 45µm.

Table 11 shows the Design of Experiment. Eight new treatments are treatment 43 to treatment 50. Each treatment was performed on 4 die. All the treatments used a small FAB value of 1.6 and small Bond Force, targeting small ball bonds with an acceptable ball shape.

Table 11 Design of Experiment for 3rd Experiment

Treatment No.	Temperature	Force	USG (current settings)	FAB	Capillary	Number of Die
43	180	10	85	1.6	BN	4
44	180	10	105	1.6	BN	4
45	180	12.5	85	1.6	BN	4
46	180	12.5	105	1.6	BN	4
47	180	10	85	1.6	HF	4
48	180	10	105	1.6	HF	4
49	180	12.5	85	1.6	HF	4
50	180	12.5	105	1.6	HF	4

5.7. Results

The pull test results from experiment showed no sign of failures with no NSOP or ball pull off. Figure 28 shows pull force distribution for the third experiment where red box plots represent bottleneck capillary treatments and blue represents high frequency capillary treatments. All have acceptable pull strength values.

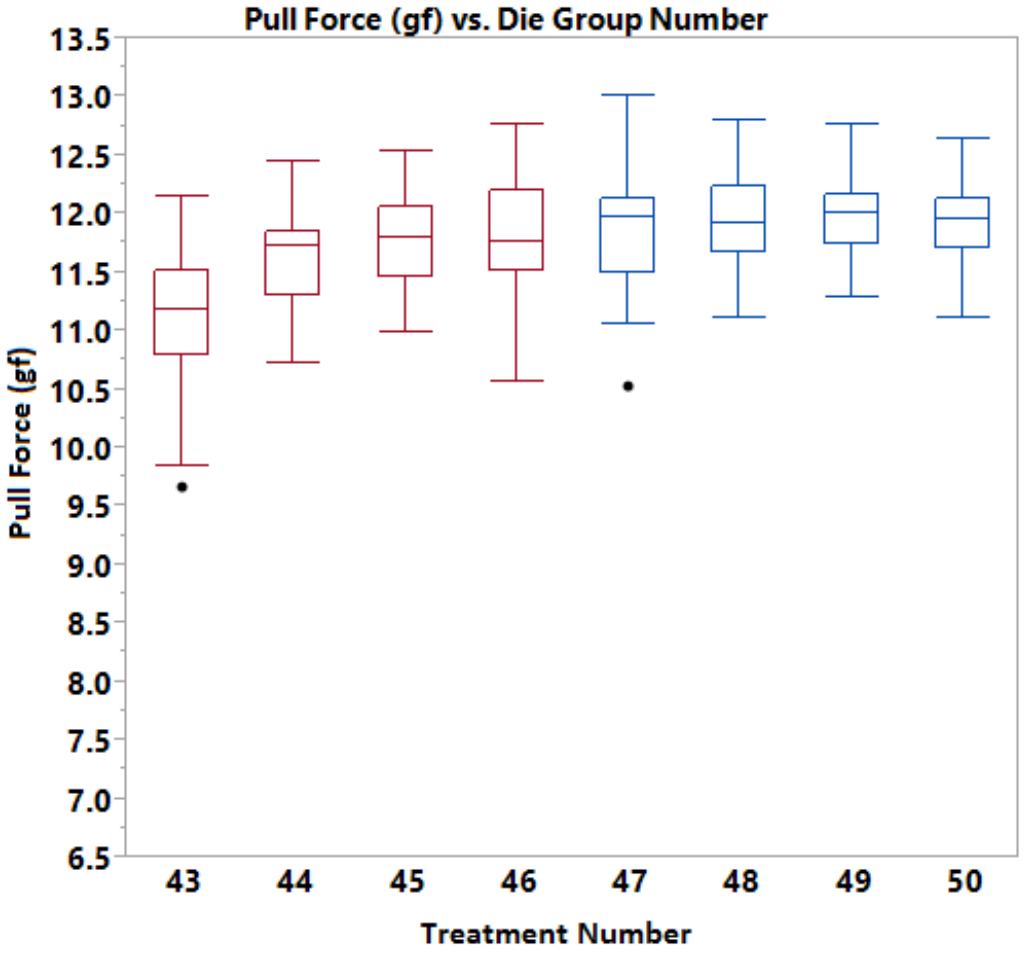

Figure 28 Experiment 3 - Pull Force vs Treatment Box Graph

Shear test and SEM photo results for experiment three showed some signs of failures, during shear test. Treatment 47 showed ball lift failures with indications of very low IMC formation, thus occasionally giving very low shear force results as seen in Figure 29 as outliers. SEM photographs acquired later revealed that treatments 44, 45, 46 and 50 have smashed ball structures, outlined by red box. Red box plot represents bottleneck capillary treatments and blue box plot represents high frequency capillary treatments.

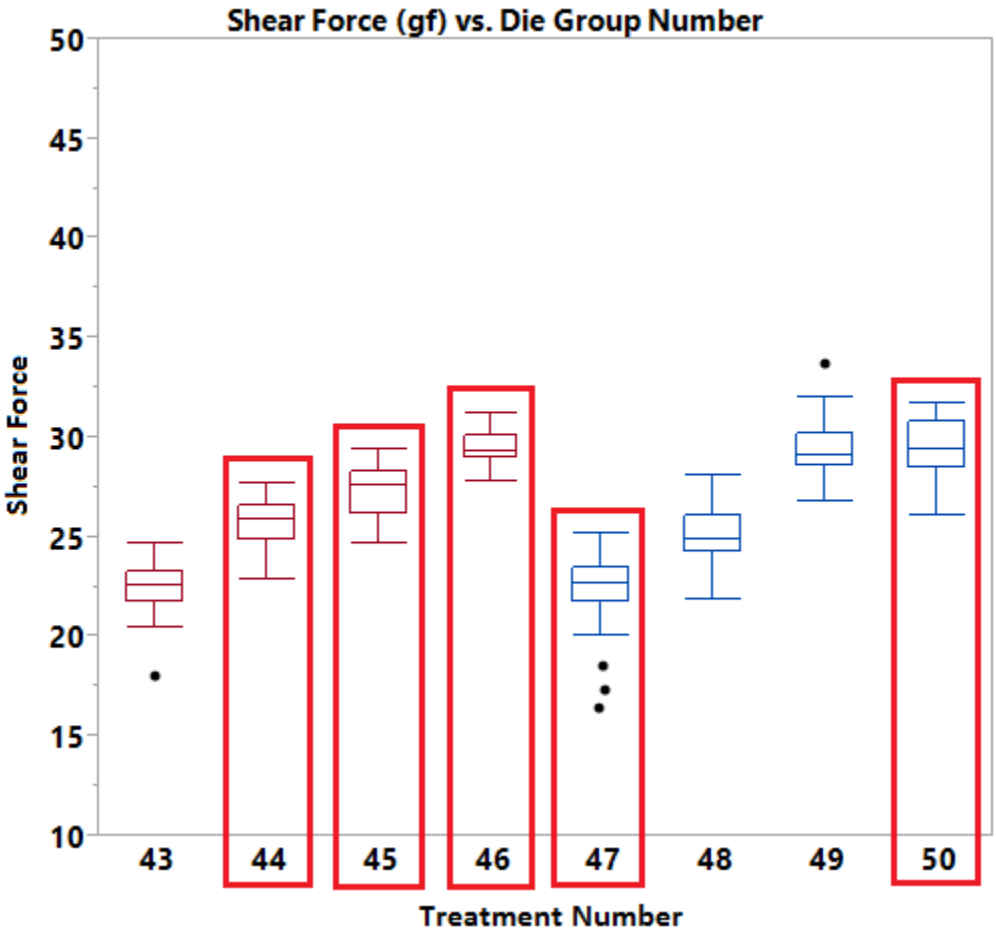

Figure 29 Experiment 3 - Shear Force vs Treatment Box Graph

5.8.Fourth Experiment

The final experiment consists of new treatments for recipe optimization of each capillary, targeting ball diameters of 55µm to 65µm. For HF, treatment 39 is considered best producing ball diameter around 55µm and treatment 26 producing ball diameters around 65µm. Similarly for BN, treatment 22 gave best bonds with ball diameter around 55µm, and treatment 28 with ball diameter around 65µm.

Taguchi Design of Experiment is used for fourth experiment. Taguchi method is structured approach to determine the best combination level for factors to yield best outcome. Tables 12 and Table 13 show the parameters, with three levels each, for each capillary.

Table 12 Taguchi 4 Factor - High Frequency Capillary

Parameter Number	Parameter	Level 1	Level 2	Level 3
1	FAB	1.9	2	2.1
2	force	15	18.5	22
3	temp	190	200	210
4	USG	85	90	95

Table 13 Taguchi 4 Factor - Bottle Neck Capillary

Patameter Number	Parameter	Level 1	Level 2	Level 3
1	FAB	1.9	2	2.1
2	force	20	25	30
3	temp	190	200	210
4	USG	90	95	100

Table 14 shows a typical Taguchi L9 design for 4 factors, the values in columns under ‘Column’ section indicated level number for that particular experiment.

Table 14 Typical Taguchi L9 Design

Taguchi L9 Design				
Experiment Number	Column			
	1	2	3	4
1	1	1	1	1
2	1	2	2	2
3	1	3	3	3
4	2	1	2	3
5	2	2	3	1
6	2	3	1	2
7	3	1	3	2
8	3	2	1	3
9	3	3	2	1

Using Taguchi L9 design 18 new treatments are designed. Table 15 shows the complete fourth experiment design.

Table 15 Design of Experiment for 4th Experiment

Treatment No.	Temp	Force	USG	FAB	Capillary	Number of Die
51	190	15	85	1.9	HF	3
52	200	18.5	90	1.9	HF	3
53	210	22	95	1.9	HF	3
54	200	15	95	2.0	HF	3
55	210	18.5	85	2.0	HF	3
56	190	22	90	2.0	HF	3
57	210	15	90	2.1	HF	3
58	190	18.5	95	2.1	HF	3
59	200	22	85	2.1	HF	3
60	190	20	90	1.9	BN	3
61	200	25	95	1.9	BN	3
62	210	30	100	1.9	BN	3
63	200	20	100	2.0	BN	3
64	210	25	90	2.0	BN	3
65	190	30	95	2.0	BN	3
66	210	20	95	2.1	BN	3
67	190	25	100	2.1	BN	3
68	200	30	90	2.1	BN	3

5.9. Result

The pull test results from the experiment showed no sign of failures with no NSOP and ball pull off. Figure 30 shows pull force distribution for the fourth experiment with blue color representing high frequency capillary treatments and red color represents bottleneck capillary treatments.

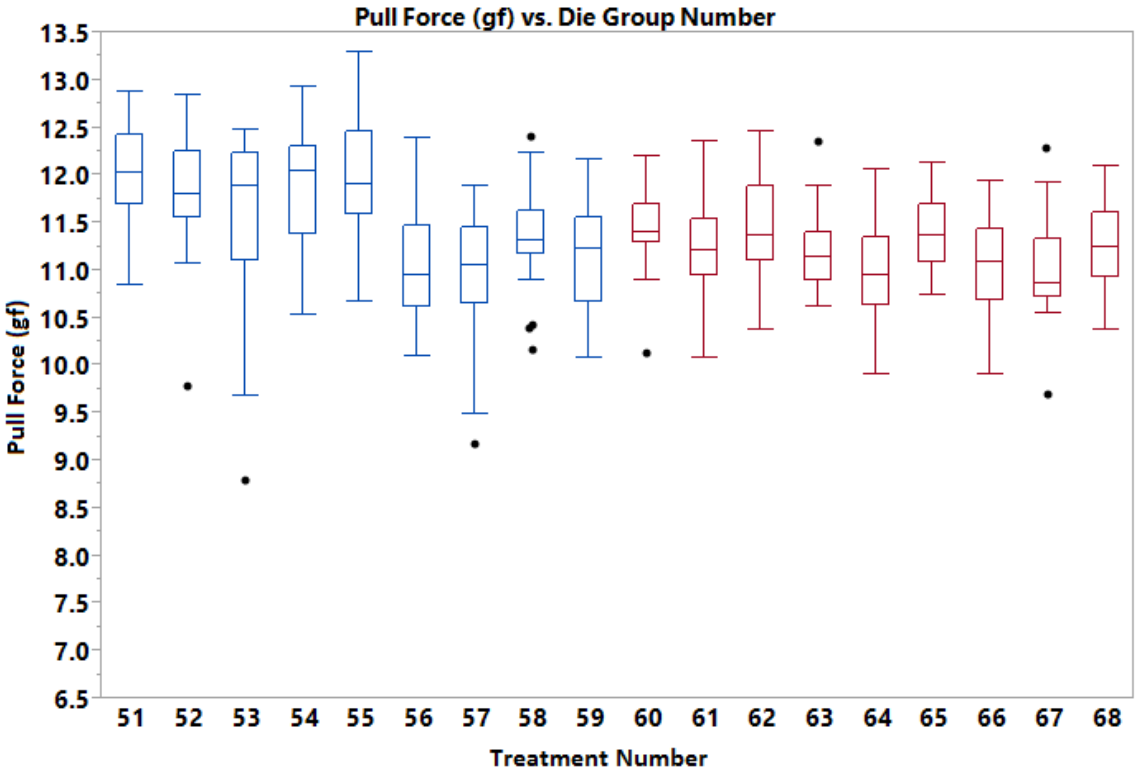

Figure 30 Experiment 4 - Pull Force vs Treatment Box Graph

Shear test and SEM photo results for the fourth experiment showed no sign of failures. Figure 31 shows shear force box plot distribution for each treatment (Red for bottleneck treatments and blue for high frequency treatments).

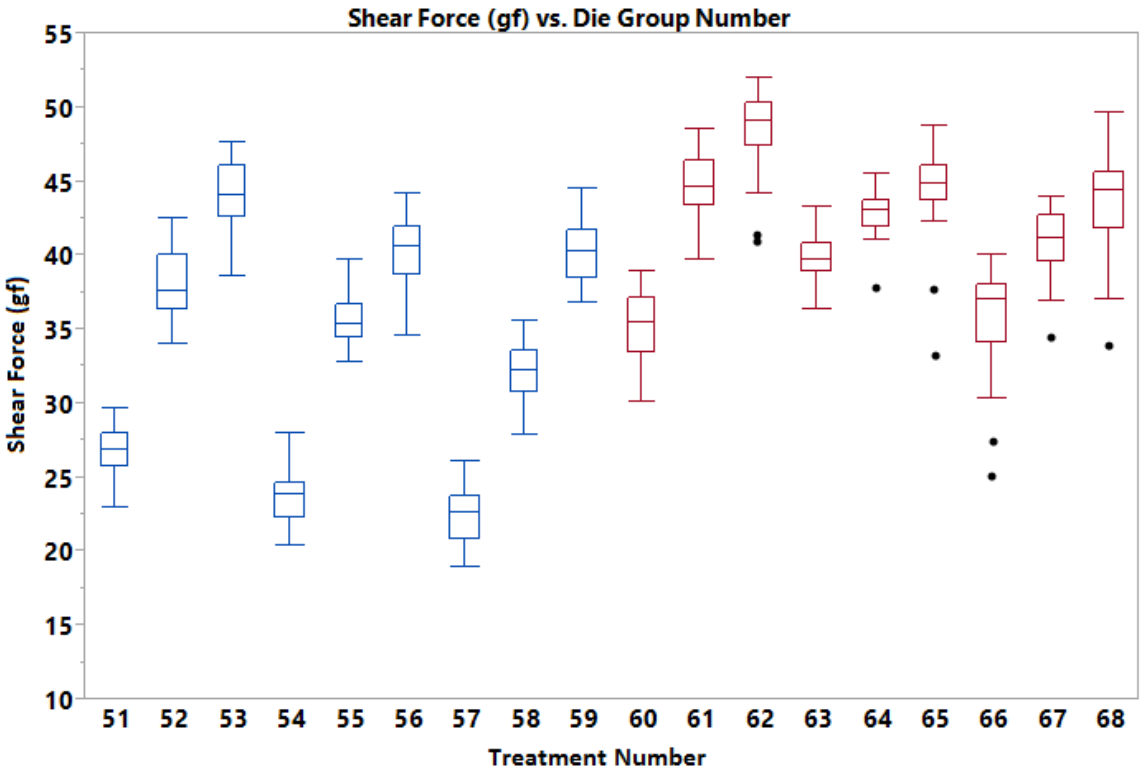

Figure 31 Experiment 4 - Shear Force vs Treatment Box Graph

Chapter 6

6. Analysis

Based on the experimental results, many different types of analysis were done to decide on the best bonding recipes, and how different factors play a role in bonding.

6.1.Shear Force VS Contact Area Analysis

The most important technique to analyze the bond strength and reliability is to measure shear force per area. A larger diameter ball bond might be giving a higher shear force due to a larger contact area. Table 16 shows the shear force per area values for all the treatments. For convenience of viewing, the force per area values are multiplied by 1000, detailed information could be found in Appendix.

Table 16 Shear Force vs Contact Area Summary

Treatment Number	Ball Diameter Optical (um)	SF/Area (1000 x gf/um)	Capillary
2	63.13	14.71	BN
3	65.83	11.26	BN
5	61.83	9.24	BN
8	53.50	13.48	BN
9	67.90	10.76	BN
12	57.67	12.98	BN
14	56.40	12.22	BN
15	61.67	9.97	BN
18	59.27	13.20	BN
19	69.73	13.73	BN
22	59.87	15.79	BN
24	65.33	12.84	BN
25	66.30	8.92	BN
27	68.77	12.26	BN
28	68.20	13.54	BN
29	66.97	13.69	BN
30	62.60	14.64	BN
36	51.10	13.82	BN
38	52.83	13.83	BN
40	52.83	15.25	BN
42	53.63	14.68	BN
43	46.00	16.62	BN
44	49.73	14.38	BN
45	47.53	16.36	BN
46	51.87	15.84	BN
60	56.93	17.21	BN
61	60.80	17.67	BN
62	66.13	17.97	BN
63	60.53	16.28	BN
64	62.27	18.20	BN
65	64.20	15.48	BN
66	61.00	16.13	BN
67	62.73	15.91	BN
68	65.00	15.27	BN

Treatment Number	Ball Diameter Optical (um)	SF/Area (1000 x gf/um)	Capillary
1	79.73	11.38	HF
4	76.37	8.22	HF
6	57.60	11.39	HF
7	59.97	7.32	HF
10	76.03	7.40	HF
11	70.40	11.52	HF
13	60.17	8.15	HF
16	55.67	12.75	HF
17	64.87	12.14	HF
20	76.50	8.46	HF
21	68.13	13.54	HF
23	72.77	12.20	HF
26	67.20	13.09	HF
31	57.60	12.67	HF
32	65.13	12.59	HF
33	62.20	13.82	HF
34	64.97	14.40	HF
35	49.90	13.04	HF
37	51.15	14.41	HF
39	53.73	14.43	HF
41	53.60	13.12	HF
47	44.20	18.76	HF
48	45.13	18.66	HF
49	47.93	18.09	HF
50	50.69	15.86	HF
51	53.27	16.33	HF
52	58.53	18.61	HF
53	63.67	17.80	HF
54	55.32	13.66	HF
55	58.07	18.57	HF
56	61.27	17.26	HF
57	55.20	13.10	HF
58	60.40	15.50	HF
59	63.20	17.33	HF

The average value of shear force per area is 12.31 (gf/um^2 x 1000). So any value below this is considered to be a low value. The following graph, Figure 32, shows all the treatments in shear force per area. Values above blue line indicate above average value and below indicate below average values. The three treatments on the right side are unexpectedly low, having a strong influence on the line slope, treatments 4, 10 and 20. After investigation by SEM photo, these treatments are the only treatments having smashed ball shapes. It's quite clear from the analysis that smashed ball gives poor shear force to area value and so should be avoided. Moreover some other treatments have too low a shear force value, as seen in the left bottom end of the graph, treatments 7, 13, and 15. Further analysis of these treatments through SEM photographs revealed that all of these treatments have fat ball shapes with large ball height. So from the observations it can be concluded that smashed balls and fat balls both cause low shear force per area and thus are not optimum for bonding. Remaining points that are lower than average although have a good looking ball shape but did not gave good bonding results so a poor ball shape confirms a bad bonding strength but good ball shape do not confirm that ball bond strength will be good as there are many other factors that could lead to poor bonding.

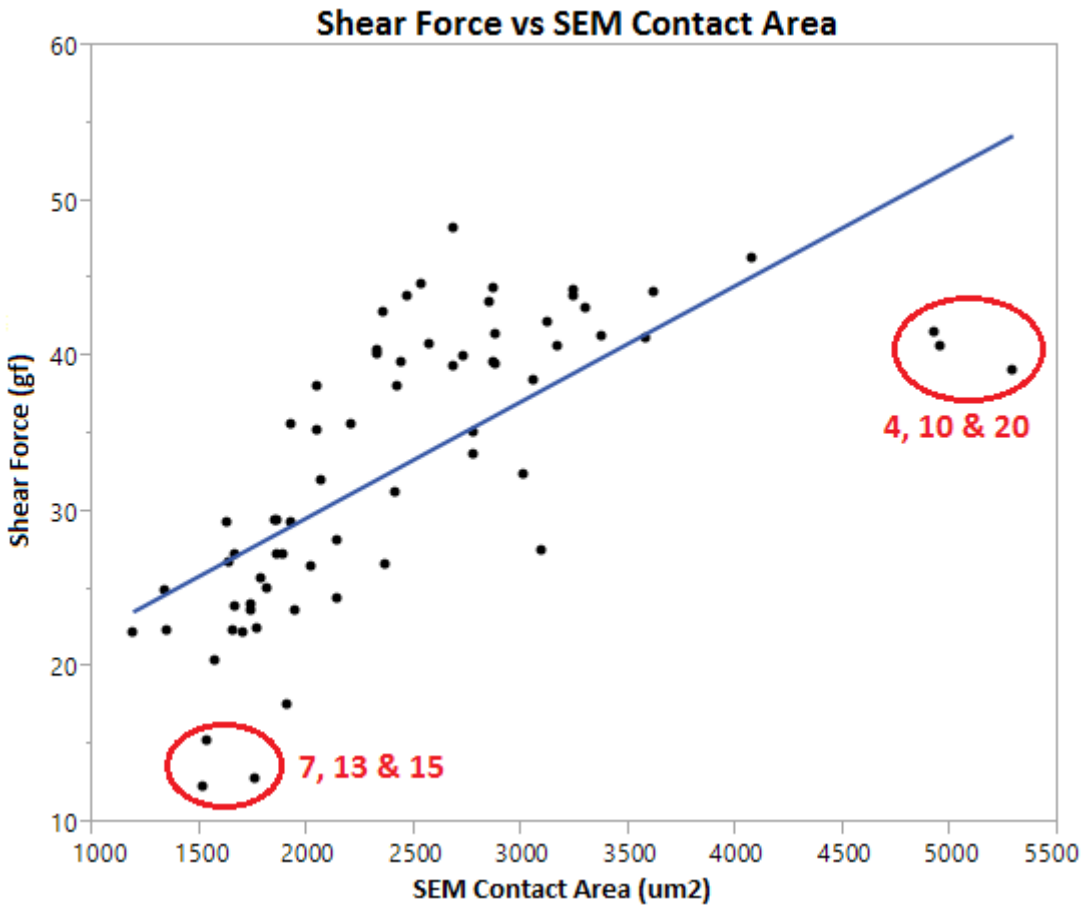

Figure 32 Shear Force vs Contact Area

6.1.1. High Frequency Capillary

Figure 33 shows shear force per area for HF only. Shear force increases with the ball contact area, as expected. The straight line is observed after removing the poorly bonded treatments marked in the previous graph.

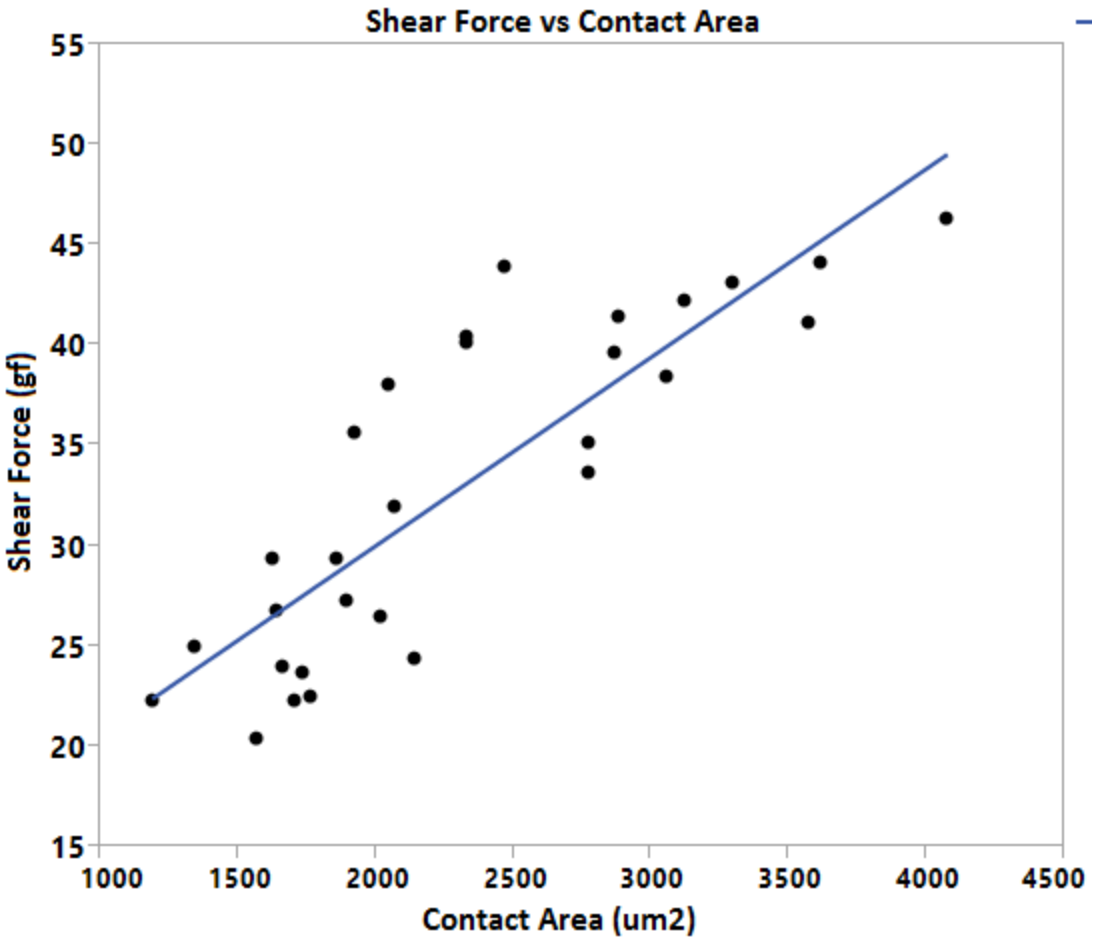

Figure 33 Shear Force vs Contact Area - HF Capillary

6.1.2. Bottle-neck Capillary

Shear force per contact area for BN is shown in Figure 34. But there are some outliers that are very far from the line fit. These treatments are 5, 25 and 62, marked by red circles. Physical analysis of the ball shapes reveals that as the treatment falls below the line they tend to have a fat ball shape, which might appear to have a good contact area, but in fact have low shear force, like treatment 5 and treatment 25. The treatments that are very far on the high side of the line, like treatment 62, have smashed ball shapes.

As the ball becomes too smashed with a nail-head shape, it gives a better shear force per area. But if the ball is smashed too much, the shear force doesn't increase with the apparent increase of contact area.

Besides identifying treatments with best strength per area, the analysis also explains that ball shape also is an important factor in bond reliability. Smashed balls and tall, fat balls both have poor bond per area strength compared to "normal looking" bond balls.

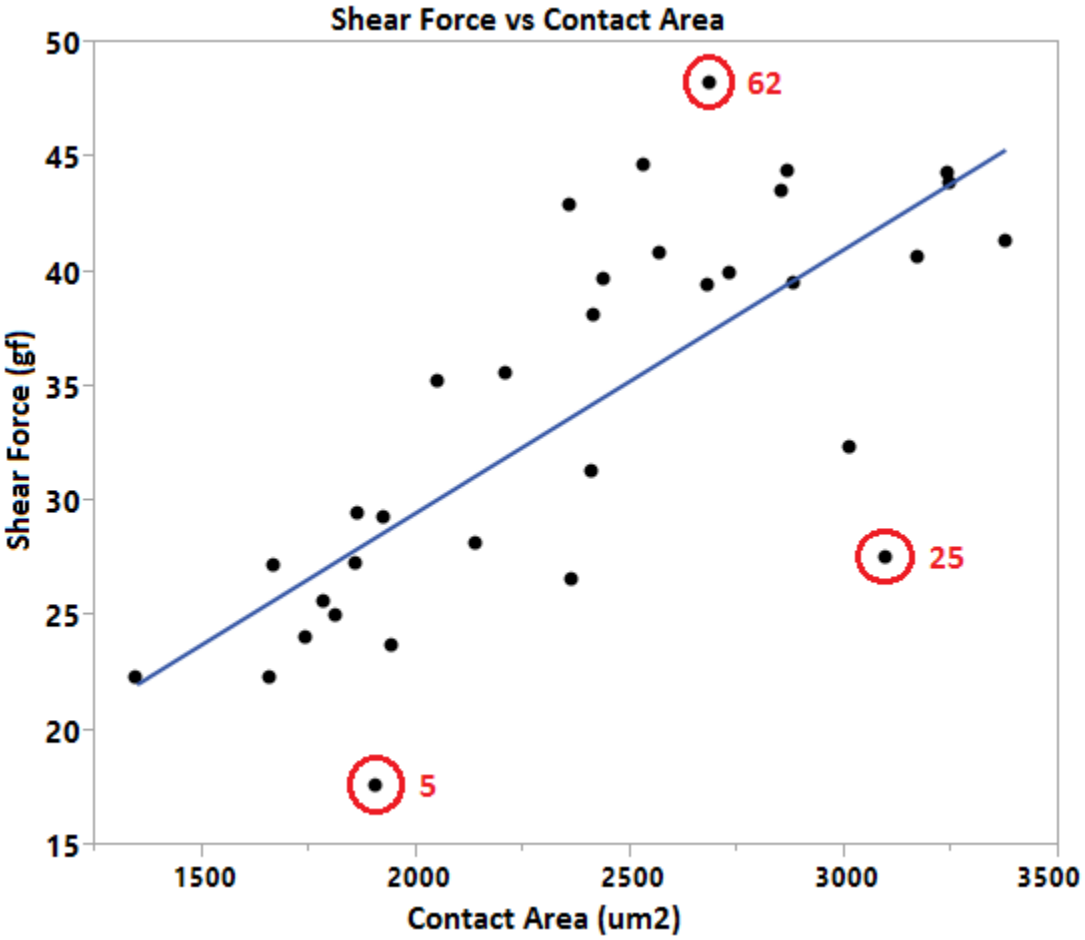

Figure 34 Shear Force vs Contact Area - BN Capillary

6.1.3. Optimum treatments

Based on the values of shear force per area, the best treatments identified for different pad sizes are as below.

For 70µm Pad size using HF: Treatment 33 and 34 are best for 70um pad size using the high frequency capillary as they produce ball bond with diameter 63µm and 64µm respectively. Also their shear force values are near 40gf with no failures found in these two treatments.

For 60µm Pad size using HF: Treatments 39 and 41 are best for 60µm pad size using high frequency capillary, giving ball bonds with diameters of 54µm, with shear forces of 27gf and 266gf, and no failures observed.

For 70µm Pad size Using BN: Treatments 2, 22 and 30 are best for 70um pad size using bottle-neck capillary, giving ball bonds with 64µm, 60µm, and 63µm diameter respectively; and shear force strengths of 39gf 38.13gf and 40gf.

For 60µm Pad size using BN: Treatments 40 and 42 are best for 60µm pad size using the bottle- neck capillary producing ball bonds with 53µm and 54µm diameter respectively. These treatments have 29gf and 27gf shear strength with no failures.

6.2. Shear Force per Area and Shear Force vs Factors

Analysis of all the factors in all experiments reveals a trend which is shown in Figure 35. Graphs in the top row are for BN, and graphs on the bottom row are for HF. Increasing Temp and USG tends to increase shear force per area for bond

whereas increase in FAB and Bond Force reduces shear force per area. This means that a large ball bond may have higher overall shear strength but shear force per area reduces. Thus smaller ball bonds are more efficient as far overall shear force is above the threshold level.

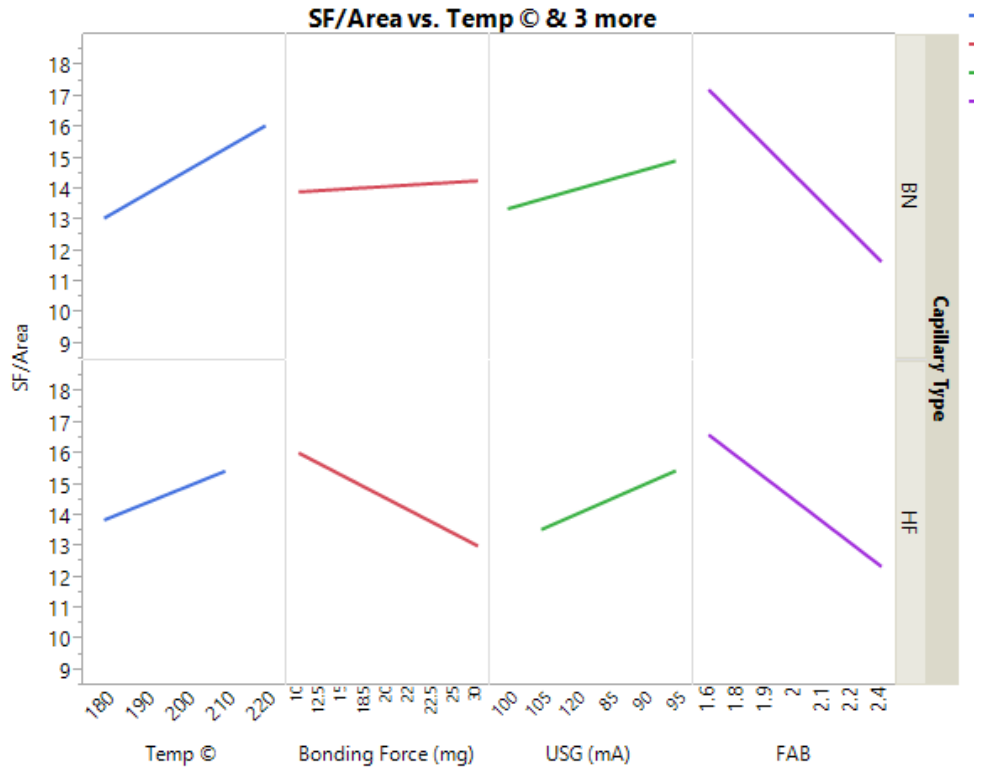

Figure 35 Shear Force per Area vs Factors

Shear force analysis reveals that increase in Bond Force increases overall shear force strength, and increase in FAB also increases shear force, for HF only. For BN, as the FAB increases the shear force decreases. BN appears to be best for small ball bonds. Also, increase in USG and Temp increases shear force strength of the bond, as shown in Figure 36.

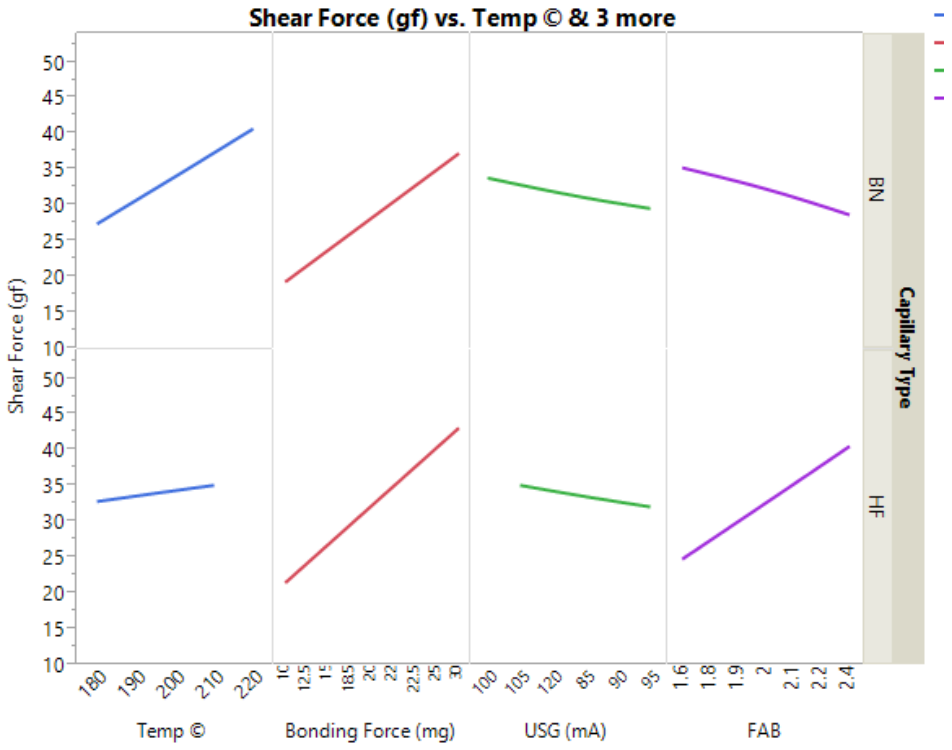

Figure 36 Shear Force vs Factors

6.3. Optimum Aspect Ratio

As discussed in the previous section, ball shape has a large effect on bond reliability. It would be a good approach to find the ball diameter to ball height aspect ratio range which will give a ball bond with good bond strength. Table 17 shows the 8 *weakest* treatments based on low shear force per area, list of ball height and ball diameter for all treatments can be found in Appendix. These treatments were already identified in last section as having either smashed or fat ball shape.

Table 17 Aspect Ratio Summary of Weakest Bonds

Treatment	Ball Diameter (um)	Ball Height (um	Shear Force per Area (gf/um2) x 1000	Aspect Ratio	comment
7	59.97	33.66	7.32	1.78	Fat
10	76.03	5.48	7.40	13.87	Smashed
13	60.17	32.84	8.15	1.83	Fat
4	76.37	8.50	8.22	8.98	Smashed
20	80.6	10.15	8.46	7.94	Smashed
25	66.30	28.02	8.92	2.37	Fat
5	61.83	32.98	9.24	1.87	Fat
15	61.67	35.10	9.97	1.76	Fat

If a ball bond having diameter to height ratio within 1.8 to 7.9 range, then these balls are more likely to be well bonded. If a ball bond has a shape with aspect ratio less than 1.8, it will be a fat ball shape, and higher than 7.9 will be too smashed. Thus, in both cases, ball bonds with weak shear force per area are observed. Therefore a ball bond with dimensions outside 1.8 to 7.9 aspect ratio will most probably has a poor shear force per area.

6.4. Shear Force vs Ball Diameter

The aim is to find an optimum recipe for each desired ball diameter. Based on these points, the best treatment for each capillary and required ball diameter will be selected.

6.4.1. Best Treatment for HF Capillary

Best treatments for HF are extracted after excluding all the treatments with failures and selecting the ones with best shear force. Figure 37 shows the best treatments for ball diameters ranging from 45µm to 65µm.

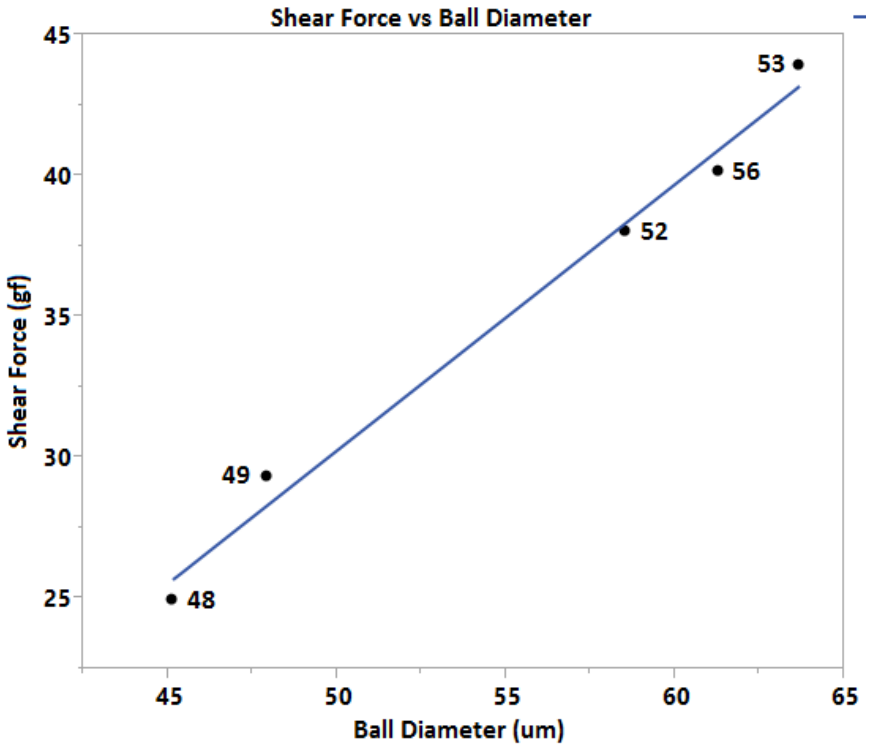

Figure 37 Optimum HF - Shear Force vs Ball Diameter

6.4.2. Best Treatment for BN Capillary

The best treatments for BN are also extracted by excluding all failures and only selecting best treatments based on shear force per area and overall bond strength. Figure 38 shows the best treatments for BN.

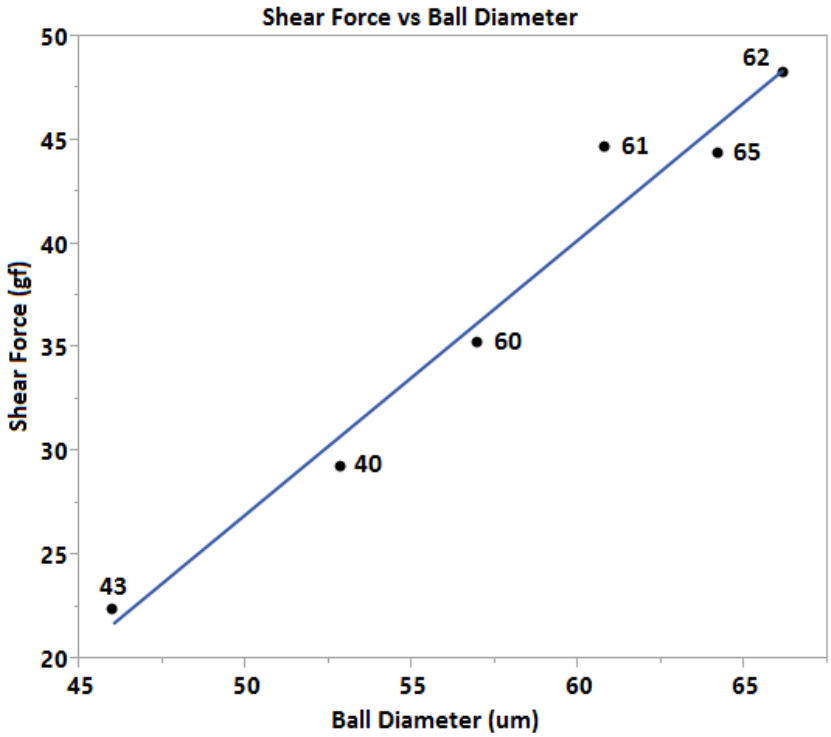

Figure 38 Optimum BN - Shear Force vs Ball Diameter

6.5. Shear Force per Area vs Optical Ball Diameter

The most important factor for analyzing bond strength is shear force per area. Figure 39 shows analysis of first 50 treatments for shear force per area vs ball diameter for HF. The graph shows that as the ball diameter increases the shear force per area decreases. Treatments 7 and 13 marked on the graph have ball pull off, so they have very low shear force per area. Also treatments 4, 10 & 20 show very low shear force per area: these treatments had smashed ball shapes. Values for shear force per area and optical ball diameter for all the treatments could be found in Appendix.

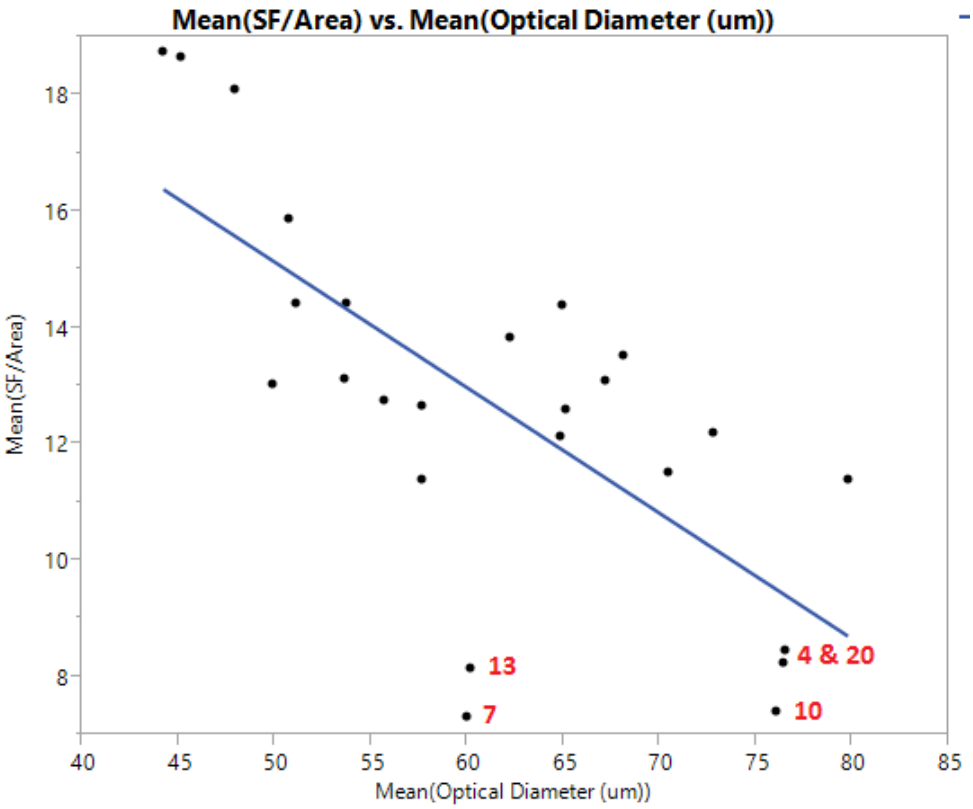

Figure 39 Shear Force/Area vs Ball Diameter for HF Capillary

Analysis of shear force per area vs ball diameter for BN in Figure 40 also reveals the same trend of drop in shear force per area with increase in ball diameter. Treatments 5, 15 and 25 are on the lower end of shear force per area and these treatments had fat ball shapes with small aspect ratio. An optimum shear force is achieved with small ball bonds, and also with large ball bonds having higher USG and Temp. Overall it is good to know that with going to smaller ball diameter a better shear force per area is achieved which will be good for future devices with smaller bond pads requiring small ball bonds.

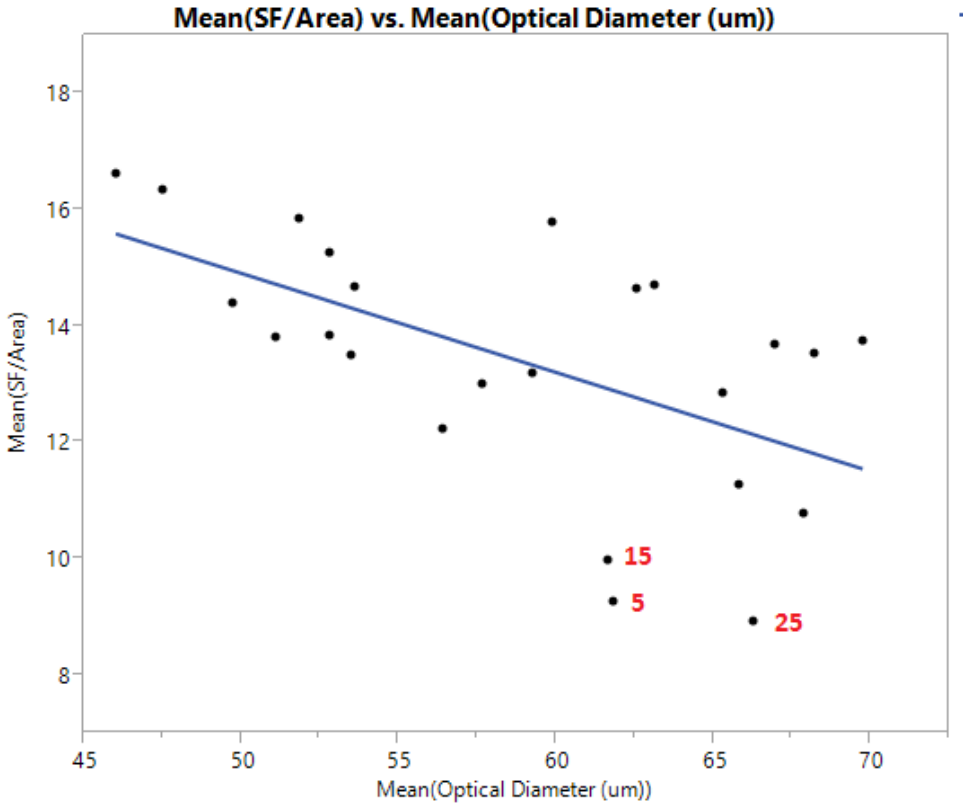

Figure 38 Shear Force/Area vs Ball Diameter for BN Capillary

6.6. Shear Force per Area vs Aspect Ratio

As discussed in section 6.3, aspect ratio of the ball bond plays an important role in ball shear force strength. Similarly aspect ratio is related to shear force per area. Figure 41 shows shear force per area vs aspect ratio for HF capillary. We see that all good treatments are clustered together in the center with aspect ratio between 2 to 6, whereas all the treatments marked in red are failures. Treatments 7 and 13 had ball pull off failures and treatments 4, 10 and 20 had smashed ball failures. Treatments 47, 48, 49 and 50 are on the higher side of shear force per area but are almost too smashed, at the edge of acceptable bond shape, and so could result in failures with a small bonding recipe

variation. Figures 42 shows the ellipse graph without the failures, and thus have a very small and precise ellipse showing that the aspect ratio of ball bonds within a tight range results in acceptable ball bonds.

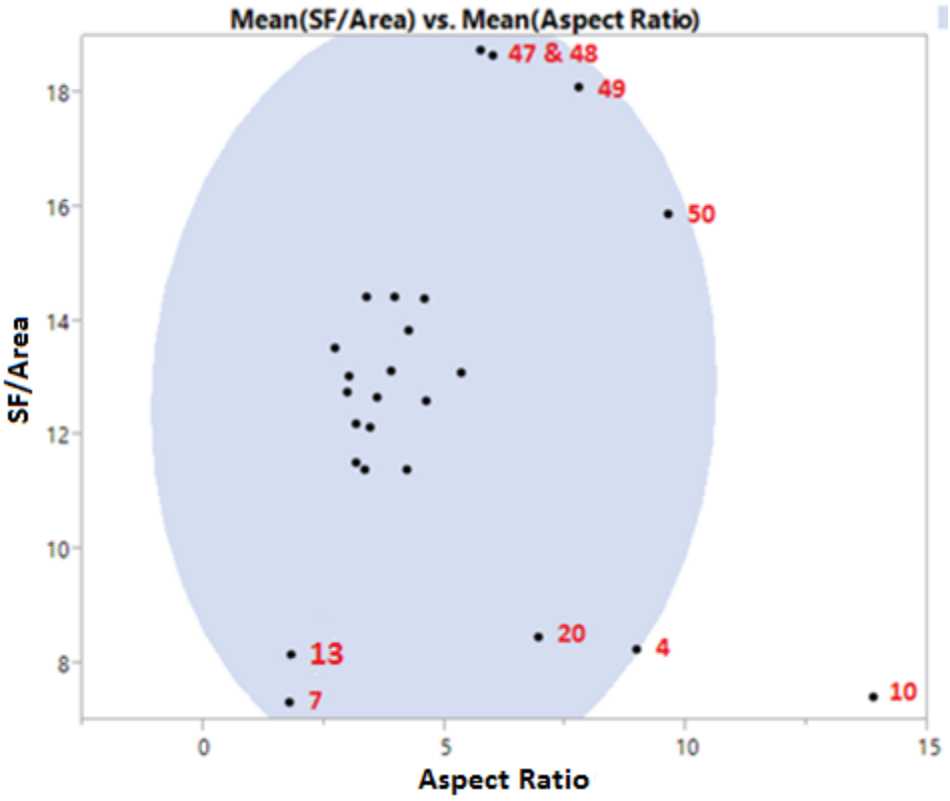

Figure 39 Shear Force per Area vs Aspect Ratio for HF Capillary

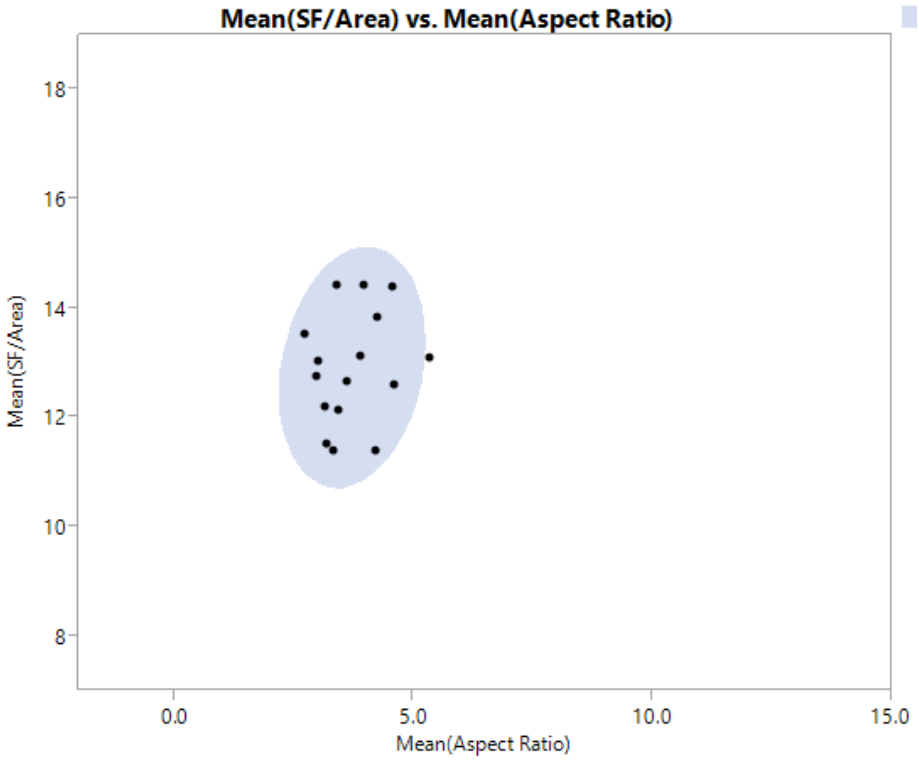

Figure 40Shear Force per Area vs Aspect Ratio for HF Capillary (Without Failures)

A similar effect is observed in Figure 43, showing shear force per area vs aspect ratio graph for BN. The outliers are marked, which treatments 5, 15 and 25 are, having fat and tall ball shapes, showing low shear force per area Treatments 44, 45 and 46 have nearly smashed ball shapes.

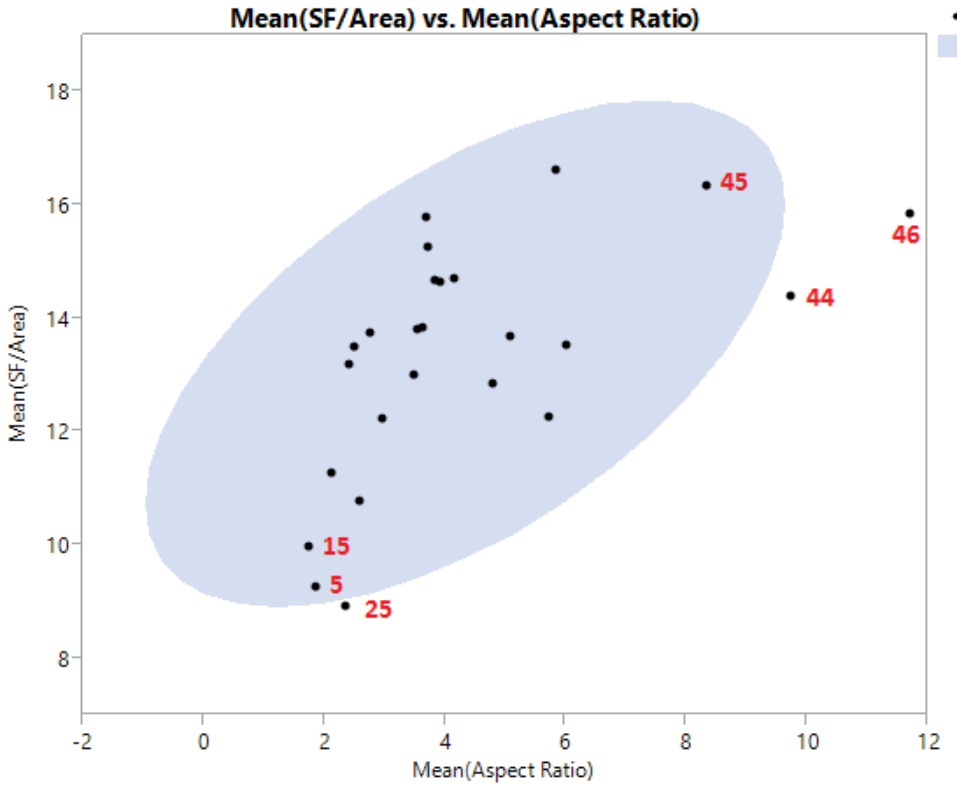

Figure 41 Shear Force per Area vs Aspect Ratio for BN Capillary

After excluding outliers and failures from the previous graph we get the small ellipse shown in Figure 44, showing that good ball bonds have aspect ratio within 2 to 6.

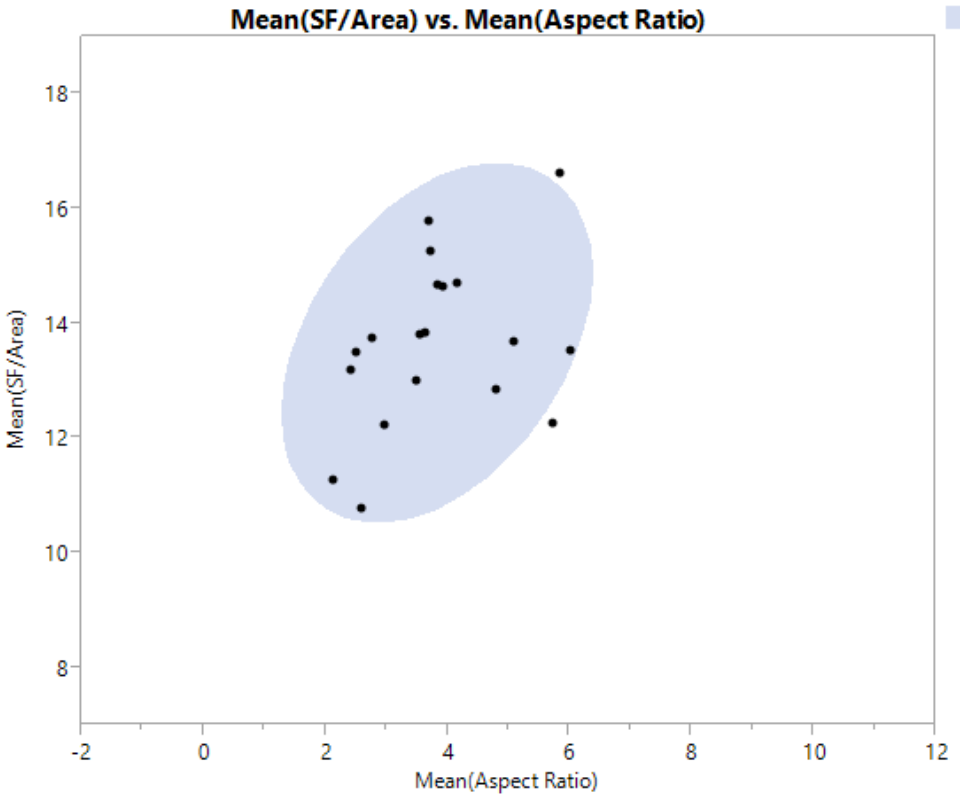

Figure 42 Shear Force per Area vs Aspect Ratio for BN Capillary (Without Failures)

6.6.1. Good Bond vs Bad Bond Ball Shapes

Based on analysis done in previous sections it is possible to predict whether the ball bond will have any failures or weak shear force strength. A ball having large aspect ratio will have a smashed structure, and balls having lower aspect ratio value will be too fat. Figure 45 shows example SEM profile images of good ball bonds and bad ball bonds. The treatments producing a fat shape or smashed shape will have poor shear force strength as identified, and a good looking ball bond between fat and smashed ball shape will be expected to give good bonding results. Ball shapes for all treatments can be found in the Appendix.

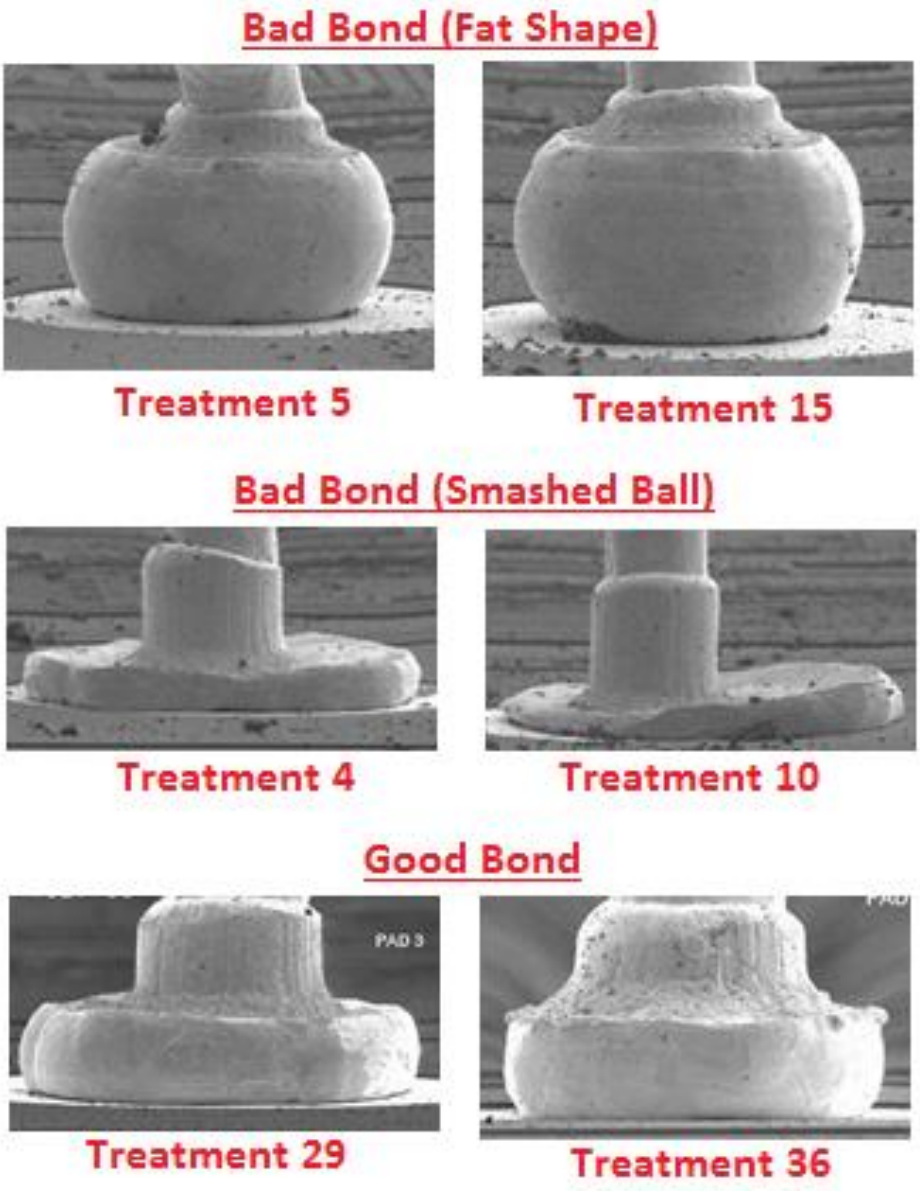

Figure 43 Ball Shapes of Bad and Good Bonds

6.7. Taguchi L9 Analysis of Factors Effect on Ball Diameter

Taguchi L9 analysis of treatments 51 to 59 is seeking the effects of different factors on ball diameter. F results are shown in Figure 46. Effects analysis shows that Bond Force plays the most important role in deciding the ball diameter, while USG, Temp and

FAB have little effect over this experiment space. Experiment surface profile 3D plots show that increasing force has a large stepping effect, which shows increase in ball diameter represented by the z-axis in these graphs. Also the graph shows that increase in FAB and USG also increases ball diameter slightly, whereas Temp has almost no effect. Results show that for each 5gf increase in bonding force the ball diameter increases by an average of 4µm in diameter when all other factors are kept constant. But for practical ball bonding, an increase in Bond Force is accompanied by an increase in FAB to give enough mass to the ball to prevent the smashed ball shape. This particular analysis is based on a small set of treatments, so the effect could vary with different levels of factors outside this Taguchi L9 analysis.

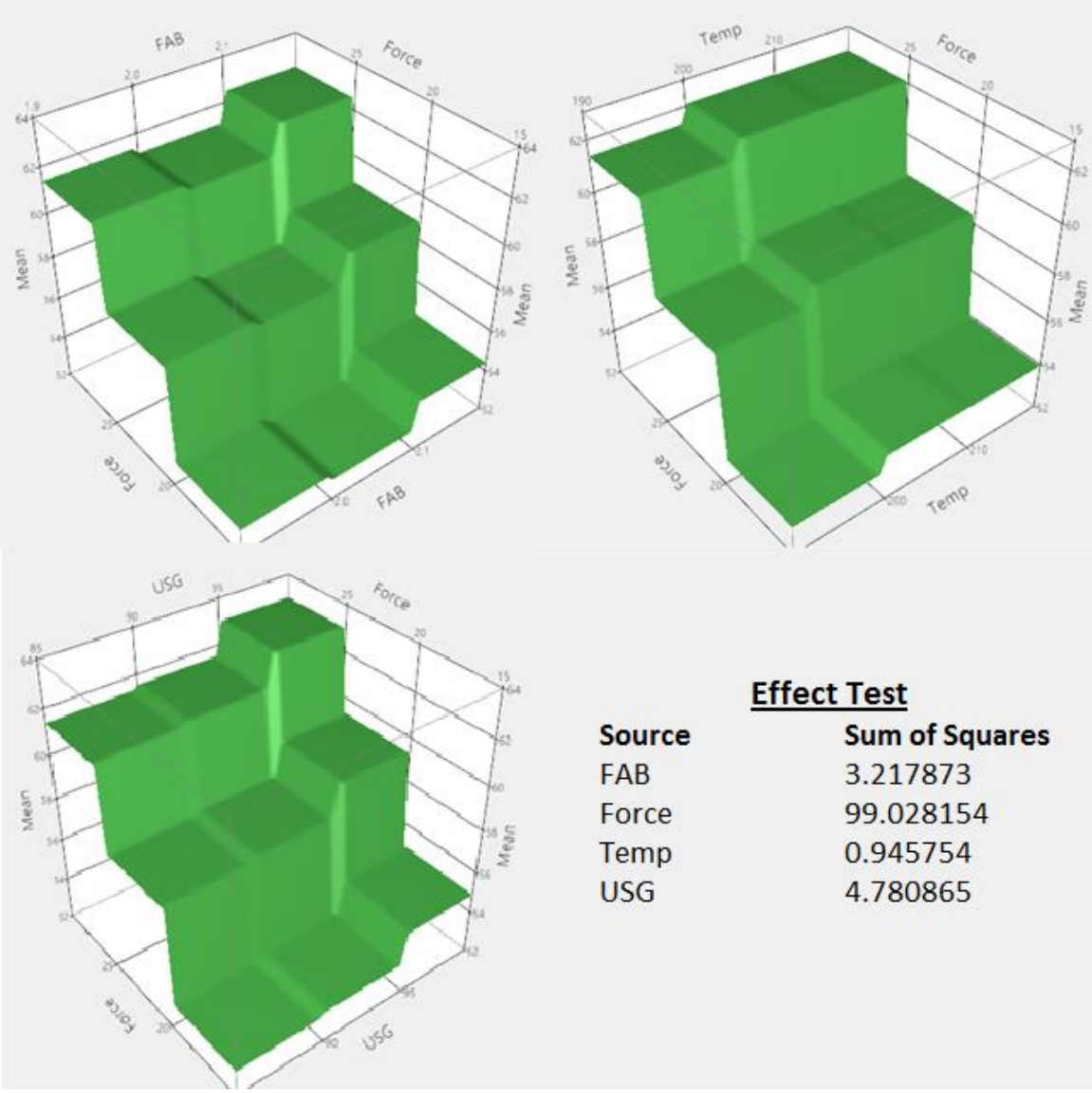

Figure 44 Ball Dia. vs Factors Surface Profile for HF capillary

Taguchi L9 analysis for treatments 60 to 68 for factors effect on ball diameter for BN also shows similar results. Figure 47 shows the effects test results and surface profile pictures. The test reveals that force plays the most important role for ball diameter, whereas FAB, USG and Temp have small and about equal effects on ball diameter. Surface profiles show that increase in Bond Force greatly increases ball diameter.

Increasing FAB, USG and Temp also increase ball diameter, but with lesser effect than Bond Force. BN results show that for every 5gf increase in Bond Force, the ball diameter increases 2to 2.5µm in diameter, with more increase in ball diameter for larger bonding forces. Also, increase in FAB and Temp linearly increases ball diameter. Increasing FAB by 0.1mil, the ball diameter increases by 1µm, but this increase in ball diameter is highest for larger FAB and lower for small FAB values. Similarly for every 10 degree Celsius increase in Temp, the ball diameter increases roughly by 1µm. These values are based on small group of experiment and could change for very large or very low FAB, Temp, USG and Bond Force values.

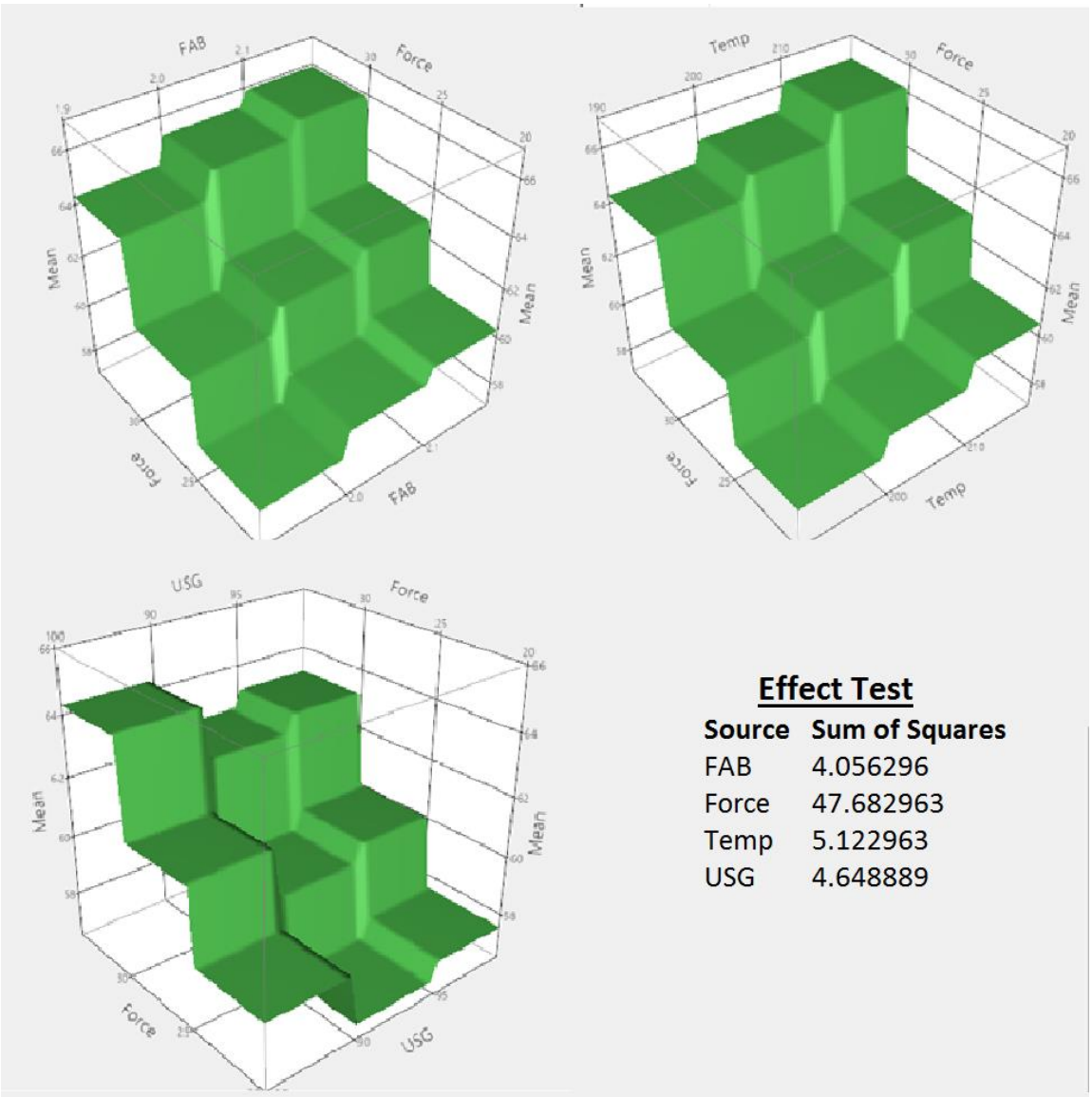

Figure 45 Ball Dia. vs Factors Surface Profile for BN Capillary

So, if there is a requirement to increase ball diameter. The best approach would be to first observe existing ball shape. If there is enough mass in the ball that could be pressed more without smashing the ball, then increasing bonding force only will be the best method. But if the ball is already a perfect shape, and an increase in diameter is required, then increasing in FAB along with Bond Force is preferred. USG and Temp

play role for small tuning. If only a little increase in ball diameter is required. Then slightly increasing USG or Temp will do the job. But it should be kept in mind that with larger FAB sizes, the effects of USG and Temp increase, so a larger increase in ball diameter may be observed for the same increase in USG and Temp.

Chapter 7

7. Conclusion

7.1. Recommendations

From the results and analysis done in previous chapter a final set of treatments are identified for each capillary type that will give best results. Based on shear force per area, shear force, pull force, ball shape and failure analysis, we extract a small set of treatments that are optimum for a required optical ball diameter, for each capillary. Optimum treatments for HF capillary and BN capillary are shown in Table 18 and Table 19 respectively, along with the bonding recipe settings.

Table 18 Optimum Treatments for High Frequency Capillary

Ball Diameter (um)	Treatment No.	Recipe				Shear Force
		Temp c°	Bonding Force (mg)	USG (mA)	FAB	
51.15	37	200	12.5	85	1.8	23.93
58.53	52	200	18.5	90	1.9	38.07
63.20	59	200	22	85	2.1	40.39
68.13	21	200	30	85	2.4	42.24
79.73	1	200	30	105	2.4	46.36

Table 19 Optimum Treatments for Bottleneck Capillary

Ball Diameter (um)	Treatment No.	Recipe				Shear Force
		Temp c°	Bonding Force (mg)	USG (mA)	FAB	
46.00	43	180	10	85	1.6	22.37
51.10	36	180	12.5	85	1.8	24.07
57.67	12	180	30	85	2	31.29
65.33	24	180	30	105	2	40.69
68.77	27	180	30	120	2	41.35

Table 20 and Table 21 show recipes to provide the needed guidance for the bonding technician to choose an appropriate bonding recipe for respective ball diameter (in convenient multiples of 5µm). Each treatment is an approximation based on existing treatments and effects due to variations of each factor. For small ball diameter, increasing Bond Force plays the most important role in increasing ball diameter. But with an increase in Bond Force, the FAB should also be increased in proportion to provide enough mass to give a good ball shape during bonding. As the ball diameter increases, the Temp and USG effects become more prominent, therefore it is preferred to increase Temp or USG other than just Bond Force, as too high a Bond Force could damage the bond pad or structure beneath it. Increasing USG for larger FAB increases ball diameter; and also for larger ball diameter with large FAB, increase in both Temp and USG will give a better shear force per area value. Therefore, in both recommended recipe tables, increase in Bond Force and FAB for smaller range of ball diameter is recommended, and for larger ball diameters, Bond Force is kept constant at 30g while USG is increased to help increase the ball diameter without other adverse effects.

Table 20 Recommended Optimum Recipes for HF Capillary

Ball Diameter (um)	Recipe				Approx. Shear Strength
	Temp c°	Bonding Force (mg)	USG (mA)	FAB	
50.00	200	12.5	85	1.7	23.00
55.00	200	18	90	1.8	32.00
60.00	200	22	85	2	37.00
65.00	200	22.5	105	2	42.00
70.00	200	30	90	2.4	46.00
80.00	200	30	105	2.4	48.00

Table 21 Recommended Optimum Recipes for BN Capillary

Ball Diameter (um)	Recipe				Approx. Shear Force
	Temp c°	Bonding Force (mg)	USG (mA)	FAB	
45.00	180	9	85	1.6	21.00
50.00	180	12	85	1.8	23.00
55.00	180	25	85	2	29.00
60.00	180	30	95	2	33.00
65.00	180	30	105	2	40.00
70.00	180	30	120	2.1	43.00

It is recommended to use the HF capillary as it tends to give slightly better bonding results overall. But for small ball diameters near 45µm or deep packages with bond pads at corners where the HF capillary can't reach easily, the BN capillary should be used.

7.2. Future Work

For future work it is desired to perform the optimum recipes suggested by the Taguchi analysis. Further experiments could be done to analyze missing treatments from the first experiment partial factorial design, with 15g bonding force, which could lead to better ball bonds with small ball diameter. Moreover a further set of experiments could be performed on the final best treatments by increasing bonding force slightly to find if even better results could be obtained. Further experiments are advised to be conducted on the recommended recipes in Table 20 and Table 21 to prove their validity, as these treatments are estimated based on experiment results and factors effects studied in this report.

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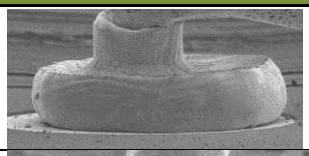
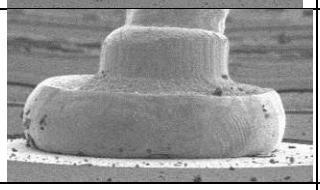
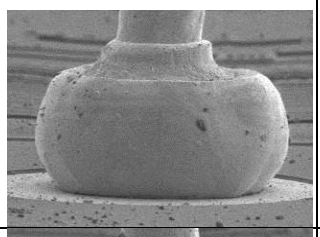
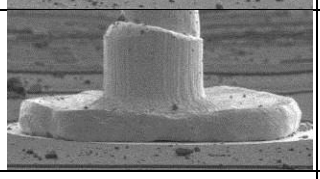
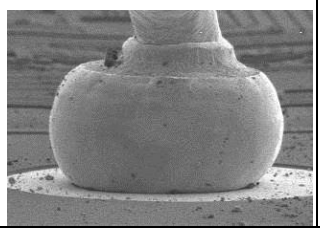
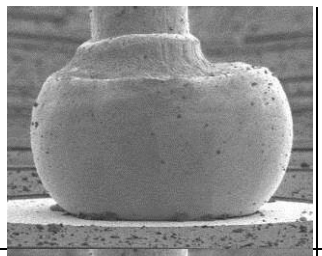
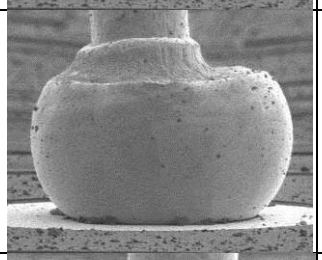
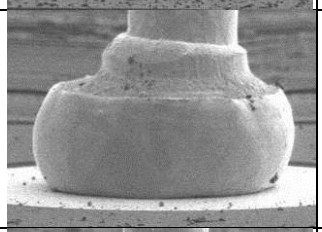
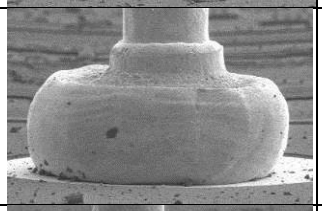
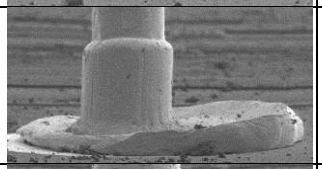
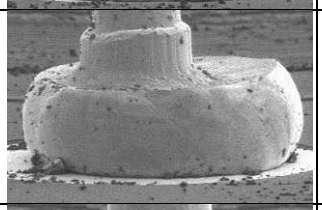
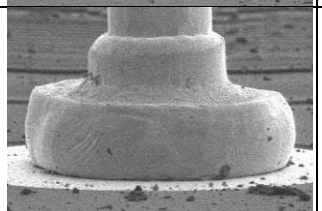
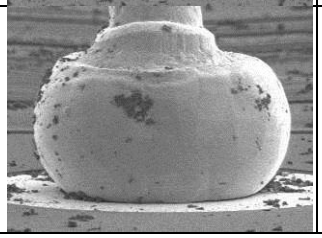
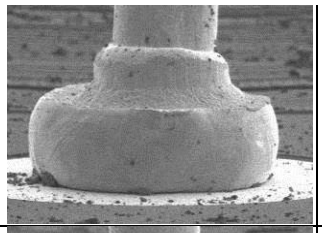
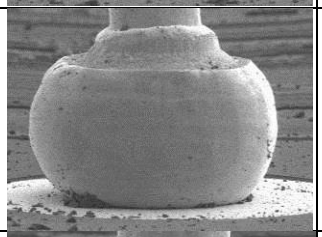
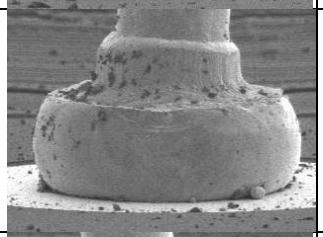
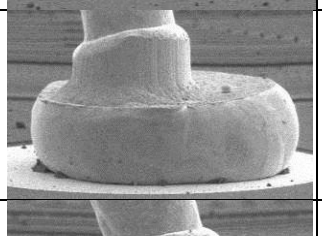
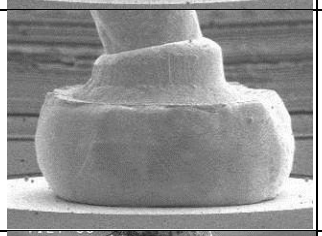
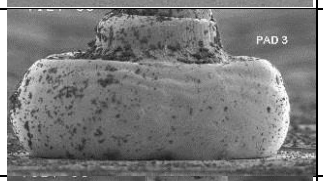
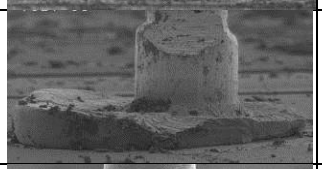
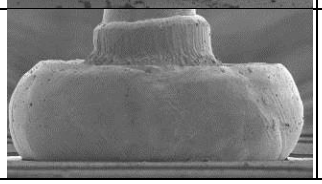
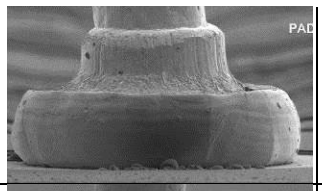
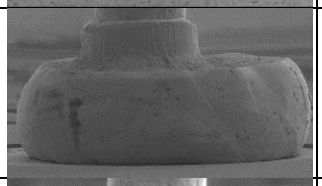
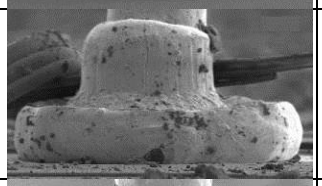
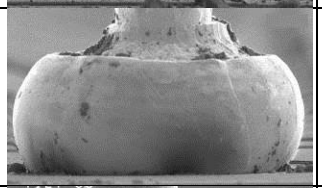
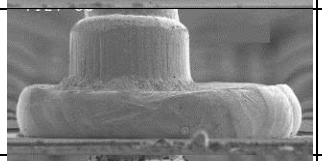
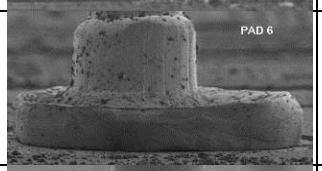
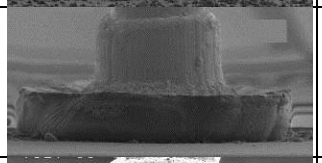
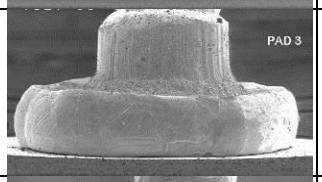
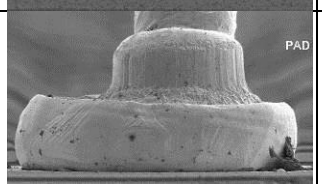
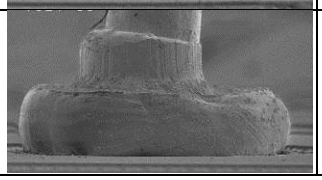
9. Appendix

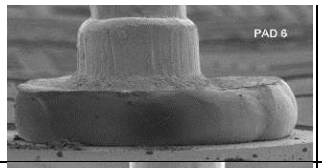
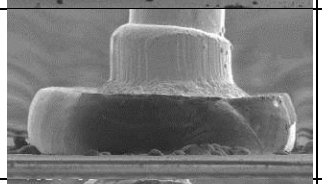
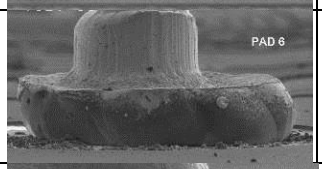
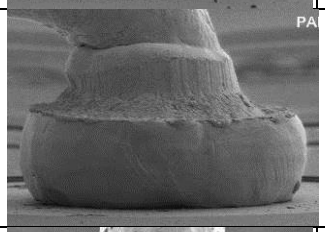
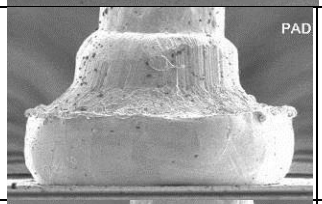
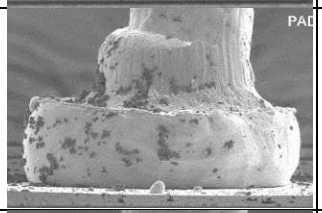
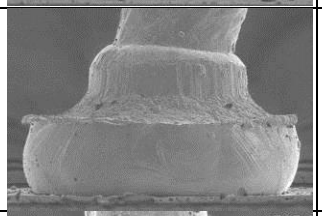
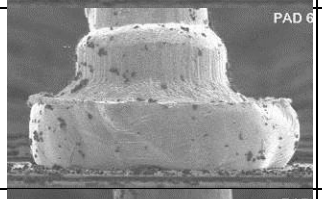
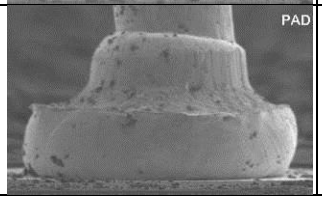
The following table shows detailed information about each treatment. All values are the mean of all readings for each treatment.

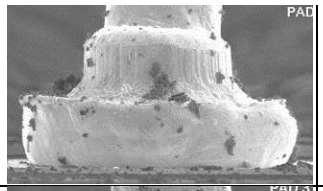
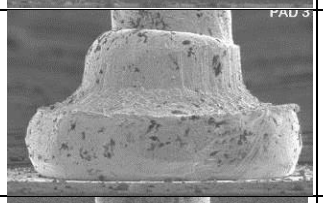
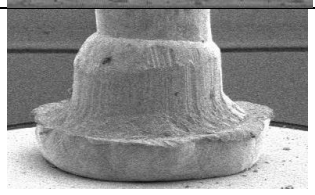
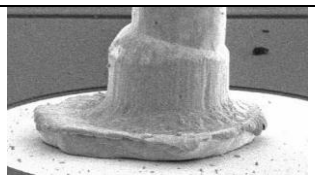
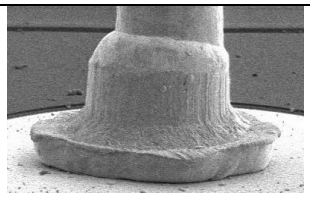
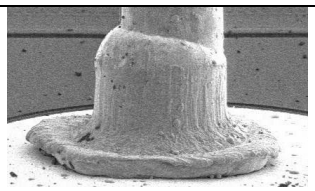
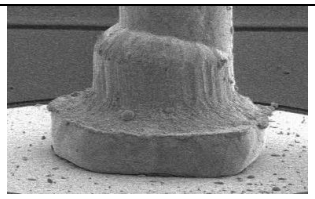
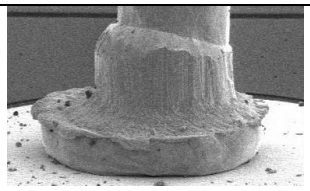
Treatment	Pull Force (gf)	Shear Force (gf)	Ball Dia. (um)	Ball Height (um)	Ball Contact Area (um2)	Shear Force per Area (gf/um2) x 1000	Ball SEM Photo	Description
1	11.46	46.36	79.73	18.92	4072.4	11.38		
2	11.66	39.43	63.13	15.15	2679.6	14.71		
3	11.40	26.59	65.83	30.92	2362.4	11.26		Fat Shaped Ball with very low shear force per area.
4	11.94	40.66	76.37	8.50	4945.2	8.22		Smashed Ball Structure
5	11.77	17.59	61.83	32.98	1903.2	9.24		Fat Shaped Ball with very low shear force per area.

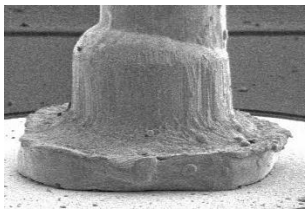
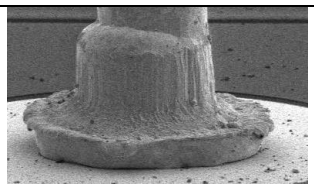
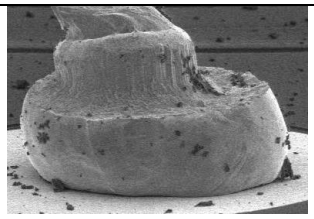
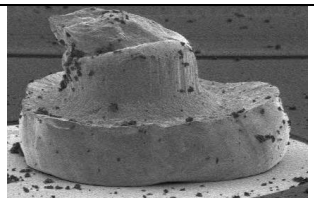
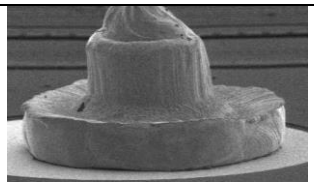
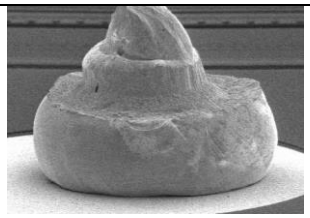
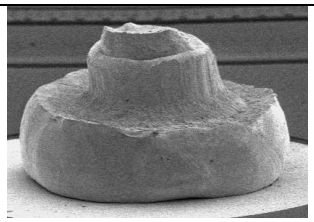
6	12.14	24.40	57.60	17.27	2142.7	11.39		
7	11.54	12.87	59.97	33.66	1758.5	7.32		Fat shaped Ball with 10 Ball Pull off failures.
8	11.98	22.34	53.50	21.39	1656.6	13.48		
9	10.56	32.38	67.90	26.12	3009.9	10.76		
10	10.91	39.11	76.03	5.48	5285.2	7.40		Smashed Ball Structure
11	10.50	41.17	70.40	22.21	3573.3	11.52		
12	10.88	31.29	57.67	16.59	2409.8	12.98		
13	10.68	12.38	60.17	32.84	1518.0	8.15		Fat shaped Ball with 19 Ball Pull off failures.

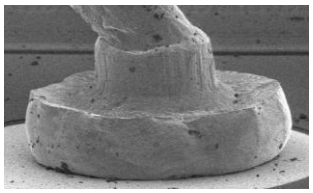
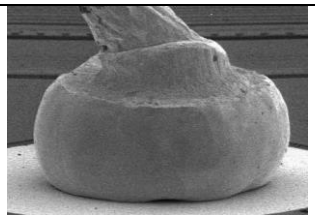
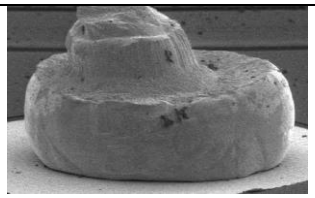
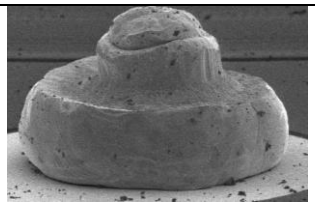
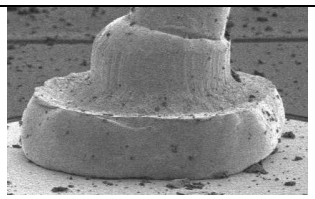
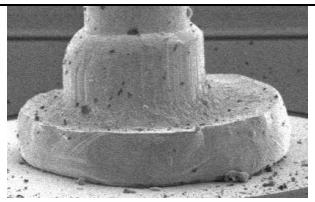
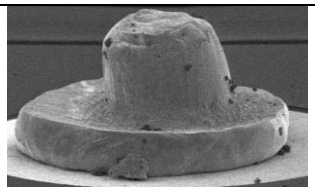
14	11.30	23.71	56.40	18.99	1940.7	12.22		
15	11.27	15.31	61.67	35.10	1535.4	9.97		
16	11.21	22.47	55.67	18.72	1762.0	12.75		
17	10.21	33.65	64.87	18.85	2771.0	12.14		
18	10.52	28.20	59.27	24.61	2137.0	13.20		
19	11.42	39.52	69.73	25.17	2878.0	13.73		
20	11.87	41.61	80.60	10.15	4916.5	8.46		Smashed Ball Structure
21	11.58	42.24	68.13	25.00	3121.1	13.54		

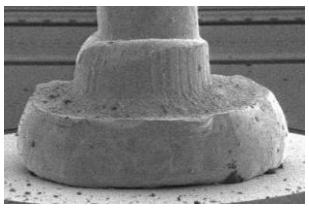
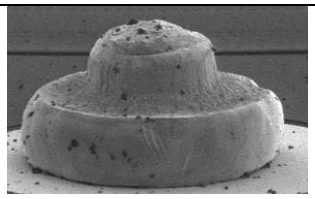
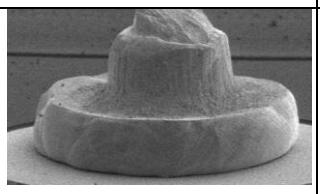
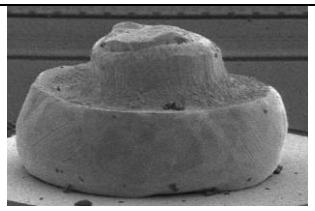
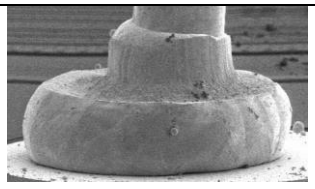
22	11.20	38.13	59.87	16.18	2414.6	15.79		
23	10.63	44.10	72.77	23.00	3615.8	12.20		
24	11.04	40.69	65.33	13.62	3169.0	12.84		
25	11.04	27.58	66.30	28.02	3092.6	8.92		
26	11.38	43.13	67.20	12.62	3294.4	13.09		
27	11.40	41.35	68.77	12.02	3372.9	12.26		Smashed Ball Structure
28	11.04	43.89	68.20	11.34	3242.6	13.54		
29	11.36	44.32	66.97	13.16	3237.9	13.69		
30	11.06	40.00	62.60	15.95	2731.3	14.64		
31	11.22	35.16	57.60	15.95	2774.4	12.67		

32	11.14	38.45	65.13	14.12	3055.2	12.59		
33	11.07	39.67	62.20	14.67	2869.5	13.82		
34	11.35	41.44	64.97	14.21	2877.7	14.40		
35	11.46	20.42	49.90	16.50	1565.4	13.04		
36	11.32	24.07	51.10	14.35	1742.1	13.82		Best 51um ball bond with BN capillary.
37	11.54	23.93	51.15	15.08	1660.9	14.41		
38	11.44	25.06	52.83	14.58	1812.2	13.83		
39	11.56	27.28	53.73	13.53	1890.1	14.43		
40	11.33	29.28	52.83	14.16	1920.4	15.25		Best 53um ball bond with BN capillary.

41	11.78	26.46	53.60	13.76	2017.3	13.12		
42	11.69	27.27	53.63	13.94	1857.4	14.68		
43	11.09	22.37	46.00	7.86	1345.7	16.62		Best 46um ball bond with BN capillary.
44	11.60	25.66	49.73	5.12	1784.1	14.38		Smashed ball shape
45	11.73	27.21	47.53	5.70	1663.8	16.36		Smashed ball shape
46	11.81	29.48	51.87	4.43	1861.2	15.84		Smashed ball shape
47	11.86	22.25	44.20	7.70	1186.0	18.76		
48	11.95	24.98	45.13	7.54	1338.6	18.66		Best 45um ball bond with HF capillary

49	11.95	29.36	47.93	6.17	1622.4	18.09		Best 48um ball bond with HF capillary
50	11.95	29.41	50.69	5.27	1853.9	15.86		Smashed ball shape
51	12.01	26.74	53.27	15.72	1637.5	16.33		
52	11.80	38.07	58.53	13.13	2045.7	18.61		Best 58.5um ball bond with HF capillary
53	11.52	43.91	63.67	10.91	2467.3	17.80		Best 64um ball bond with HF capillary
54	11.89	23.70	55.32	17.82	1734.5	13.66		
55	11.96	35.67	58.07	16.14	1921.3	18.57		

56	11.02	40.15	61.27	14.93	2325.6	17.26		Best 61um ball bond with HF capillary
57	10.95	22.28	55.20	22.10	1700.8	13.10		
58	11.36	31.99	60.40	18.99	2064.0	15.50		
59	11.14	40.39	63.20	18.35	2329.8	17.33		
60	11.43	35.26	56.93	13.45	2048.6	17.21		Best 57um ball bond with BN capillary
61	11.27	44.69	60.80	11.87	2529.8	17.67		
62	11.41	48.25	66.13	9.86	2685.1	17.97		Best 66um ball bond with BN capillary

63	11.20	39.66	60.53	15.72	2437.0	16.28		
64	11.00	42.91	62.27	15.45	2356.9	18.20		
65	11.41	44.38	64.20	13.29	2867.4	15.48		Best 64um ball bond with BN capillary
66	11.06	35.59	61.00	19.25	2206.5	16.13		
67	11.01	40.84	62.73	17.29	2567.1	15.91		
68	11.26	43.50	65.00	17.61	2849.0	15.27