Bond Strength Optimization of Silicone Thermally Conductive Adhesives for Heatsink Attachment

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Abstract

Silicone thermal interface materials (TIM) are used to bond heatsinks on many critical components in server card assemblies in typical industry systems. Silicone TIMs have excellent high temperature mechanical stability and resilience. Applications with operating temperatures above 90 degrees Celsius (C) can exhibit mechanical degradation with some acrylic or epoxy TIM adhesives. Silicones also have a low elastic modulus which enables reliable bonding of materials with differing coefficients of thermal expansion (CTE's). Silicone TIM adhesives generally require thermal cure activation, and as such are becoming increasingly difficult to use on some applications with temperature sensitive components (TSC) on printed circuit board assemblies (PCBAs). Future applications are driving the need to find the minimum cure temperature coupled with the minimum acceptable cure strength. With a silicone thermal interface material adhesive, one can optimize the cure strength based off the combination of cure temperature and surface roughness. This work focuses on varying multiple thermal bonding contributors in order to find the best combination for specific applications. One goal of this work was to provide a roughness parameter that can be used to offer optimal heatsink surface characteristics for consistent TIM bonding. Copper and aluminum are the most common heatsink materials, therefore silicone TIM was applied between these material surfaces and bond strength was evaluated by shear testing. The parameters evaluated that affected bond strength had a range of surface roughness, cure temperature, and cure time settings. Surfaces were prepared with sandpaper of various grit values. The resulting surfaces were characterized to determine average surface roughness (Ra) and peak count (RPc). Surfaces were also evaluated using scanning electron microscopy. All of the data shows that roughness has the greatest effect on resulting bond strength, followed by cure temperature. Cure time had a minimal effect on the final results as long as the cure time was greater than the minimum recommendation provided by the TIM supplier. The results show that samples with a coarse grit sanded finish did not perform well, despite the relatively rough appearance (and high Ra value). The smoother appearing, fine grit sanded finish provided the best bond strength. The smoother grit finish had a higher micro-roughness (as measured by the RPc value) than the coarse grit. In addition, a higher cure temperature produced a higher bond strength, as expected.

I. Introduction

Today's high-performance servers are designed with multiple processor and controller devices packaged into a relatively small system footprint. The high packaging density and power dissipation of these devices presents significant thermal and mechanical design challenges. Often densely packed devices do not have room for mechanically retained heatsinks, which requires use of thermally conductive adhesives to bond heatsinks to power dissipating devices. In order to meet the long service life and reliability targets of these systems, silicone adhesive thermal interface materials (TIMs) are typically required. Silicone TIMs provide excellent reliability due to their low elastic modulus and excellent high temperature stability. Commonly used acrylic TIMs have limited resilience, higher elastic modulus, and will degrade when exposed to high temperature operations or thermal cycles.[1] Silicone TIM adhesives generally require thermal cure activation, where higher temperatures generally provide optimum adhesion.[2] This presents a challenge for many new applications due to various strict component limitations of temperature sensitive components (TSCs).[3] Lower cure temperature limits will require more careful process and incoming material controls to ensure adequate mechanical strength. This work focused on defining optimum surface roughness and cure conditions to allow successful bonding of heatsinks onto printed circuit board assemblies (PCBAs) in all cases. It was expected, based on historical experience, that surface roughness parameters would have a strong effect on resulting bond integrity. The results of this work confirmed that roughness is a significant factor, but illustrate the difficulty in control and specification of proper surface conditions for optimum bond strength. The conventional roughness specification (Ra) used by most of the industry today does not ensure optimum surface conditions for bonding. Some alternative micro-roughness metrics with good correlation to bond strength have been identified.[4-6]

a. Effect of Surface Finishes on Bond Strength

Heatsink surface finish has been identified through historical bond performance tracking as a very significant factor. Figure 1 shows the micro-roughness characterization (Ra with minimum cutoff filter applied) of several good and poor performing heatsinks from suppliers A through E. Red bars on the chart represent poor performing heatsinks. Micro-roughness and cutoff filters are discussed in more detail below in section **III b**.

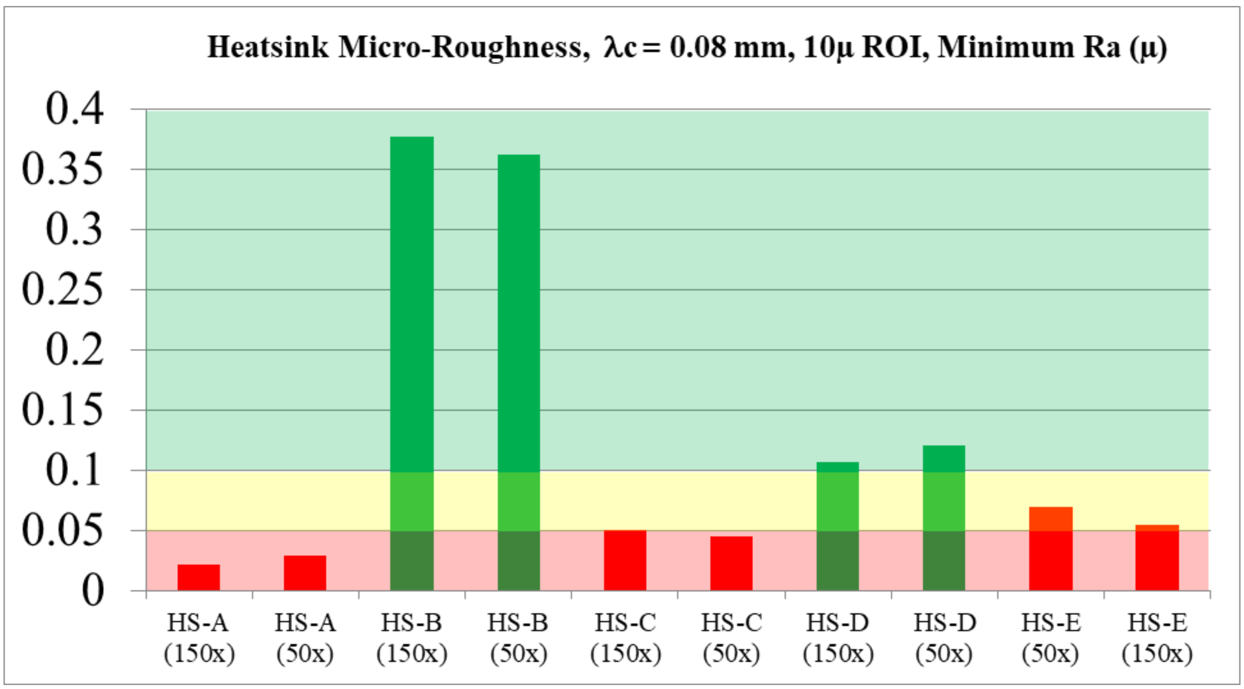

Figure 1: Micro-roughness Measurements for Heatsinks with Good / Poor Bond Performance

Figure 2 shows the poor correlation to conventional roughness measurements on these same heatsinks.

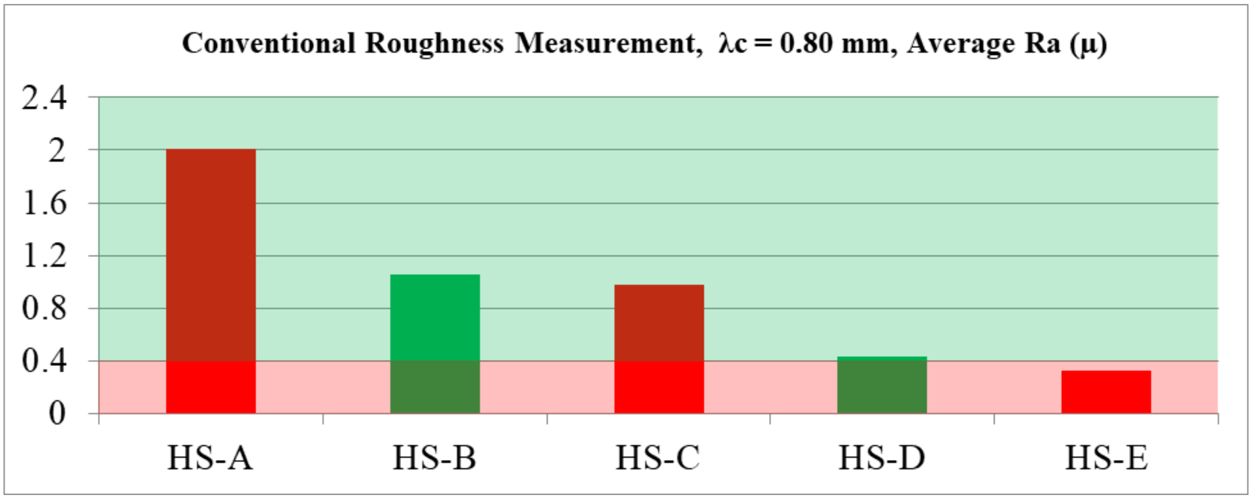

Figure 2: Standard Roughness Measurements for Heatsinks with Good / Poor Bond Performance

b. Design of Experiment

The intent of this project was to investigate the effect of temperature and time on the curing parameters of silicone TIM in order to establish product process limits. Table 1 shows some of the material properties of this silicone TIM. Surface roughness was also expected to be a critical parameter. Thus, the following parameters were evaluated in a design of experiments (DOE);

- Each Sample Group has 1 Aluminum (Alloy 6063 T5) and 1 Copper (Grade C110)Block
- Each Block in a Sample Group was finished using the Same Grit Sandpaper
- DOE Parameter 1: Sandpaper Grit (150, 220, 600)
- DOE Parameter 2: Cure Temperature (95, 100, 105, 110, 120 °C)
- DOE Parameter 3: Cure Time (40, 100, 150 minutes)

Table 1: Properties of the Silicone TIM Adhesive Used in This Study

Property	**Value**
Adhesive Cure Options	90 minutes at 100°C 30 minutes at 125°C
Operational Temperature Range	-45 to 200°C
Unprimed Adhesion – Lap Shear (Al)	4.5 MPA

Table 2 shows the DOE with the different number of samples with each set of parameters.

Table 2: Design of Experiments Plan

Roughness (Sandpaper Grit)	**N1 (600 grit)**	**N3-N5 (220 grit)**	**N6-N7 (150 grit)**	**N1 (600 grit)**	**N3-N5 (220 grit)**	**N6-N7 (150 grit)**	**N1 (600 grit)**	**N3-N5 (220 grit)**	**N6-N7 (150 grit)**
Cure Temperature (Deg C)	**40 Minutes**	**40 Minutes**	**40 Minutes**	**100 Minutes**	**100 Minutes**	**100 Minutes**	**150 Minutes**	**150 Minutes**	**150 Minutes**
95	1	1	1	1	1	1	2	1	2
100	1	1	1	1	1	1	1	1	1
105	1	1	1	1	1	1	1	1	1
110	1	1	1	1	1	1	1	1	1
120	2	1	2	1	1	1	1	1	1

II. Sample Surface Preparation

Each sample pair in this DOE consisted of one copper (Cu) and one aluminum (Al) block of equivalent surface finish, bonded together. The pair of blocks was bonded with silicone TIM material, with a bond area of roughly 1 square inch (6.45 cm^2). Both the Cu and Al blocks were divided into 3 grit paper groups (150, 220, and 600). Each block was sanded with an orbital sander running 12000 rpm for 30 seconds. Each sample pair was sanded with the same grit sandpaper, but resulting roughness varied somewhat due to different material properties of the Cu and Al blocks. All sanded surfaces were cleaned with isopropanol (IPA) and low-lint wipes.

III. Roughness Characterization

To obtain consistent heatsink bond strength, a roughness parameter that characterizes the surface condition is necessary. Average surface roughness (Ra), peak count (RPc), micro-roughness, and qualitative scanning electron microscopy (SEM) were used to evaluate surface finishes. Of the parameters evaluated in this study, surface roughness had the greatest effect on resulting bond strength.

a. Mean Surface Roughness

The mean surface roughness is defined as the arithmetic average value of the roughness profile. Ra is a valuable term for describing the overall surface height variation.[4] The surface roughness for each copper and aluminum sample was measured to quantify to the surface condition prior to silicone TIM application. The Ra was measured at a magnification of 20x, and 3 measurements were taken from each sample. The distribution of roughness values for each grit level are presented in Figure 3 below.

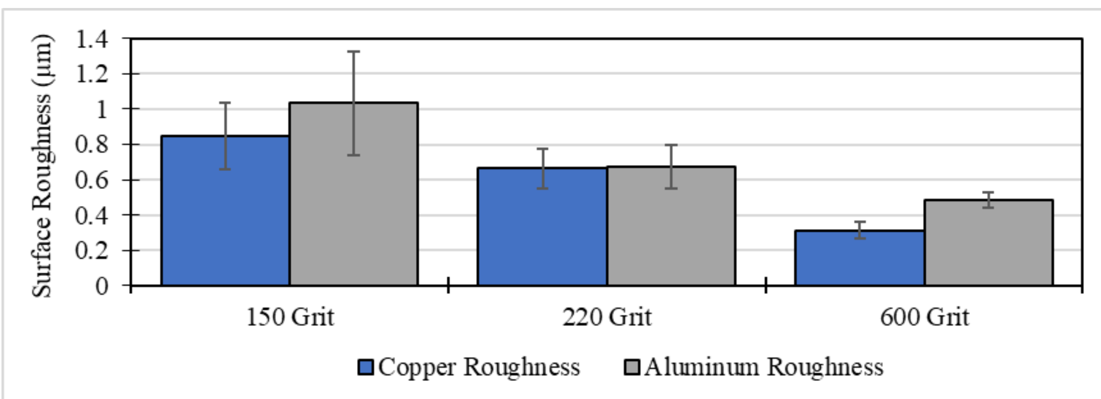

Figure 3: Histogram of Average Surface Roughness for Each Metal Sample

As the grit level increased, the surface roughness decreased. This was expected because a finer grit should yield a smoother surface. Additionally, for all samples, the measured Cu surface roughness was lower than the Al Ra. This was also predicted because often Cu is a softer more malleable metal, when compared to Al.

b. Micro-Roughness

Similar to Ra, micro-roughness was measured to characterize the surface condition of both the copper and aluminum samples. These measurements were conducted at a magnification of 150x to evaluate the roughness on a micro scale. Additionally, a cutoff filter (λc) of 0.08 mm was used. The cutoff filter is used to separate the surface waviness from the surface roughness. The difference between surface waviness and roughness is depicted in Figure4.

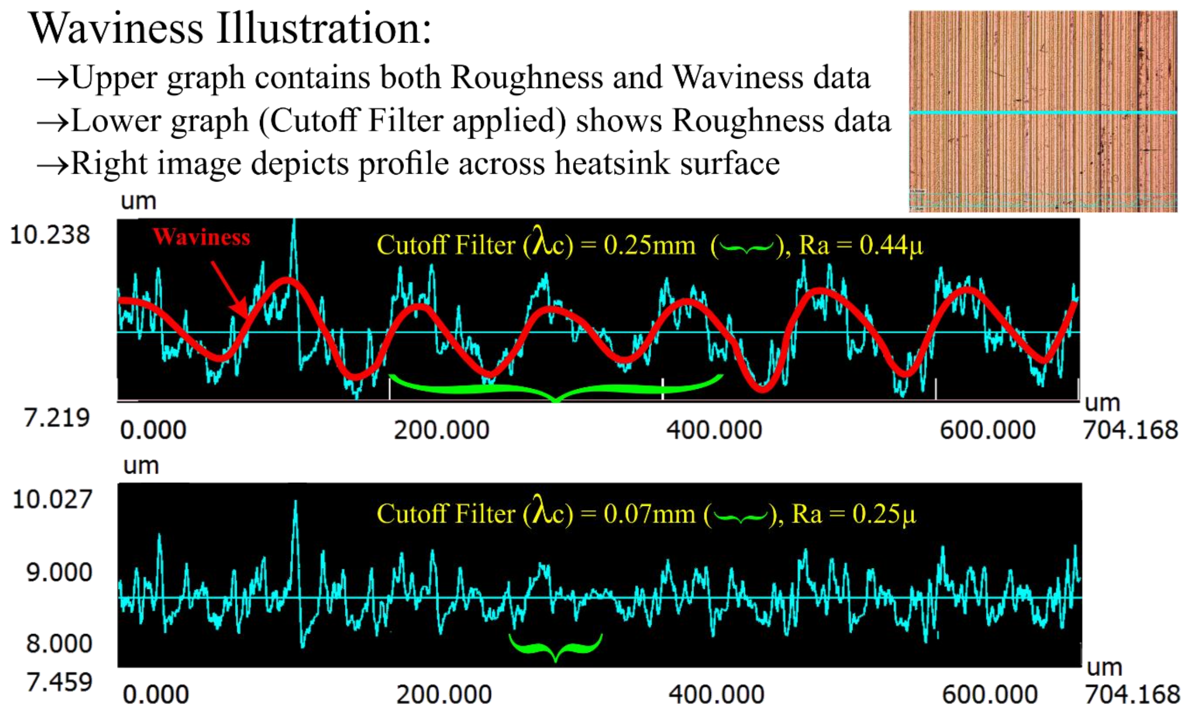

Figure 4: Examples of Waviness and Roughness Profiles

The average micro-roughness values for each grit level are presented below, in Figure 5.

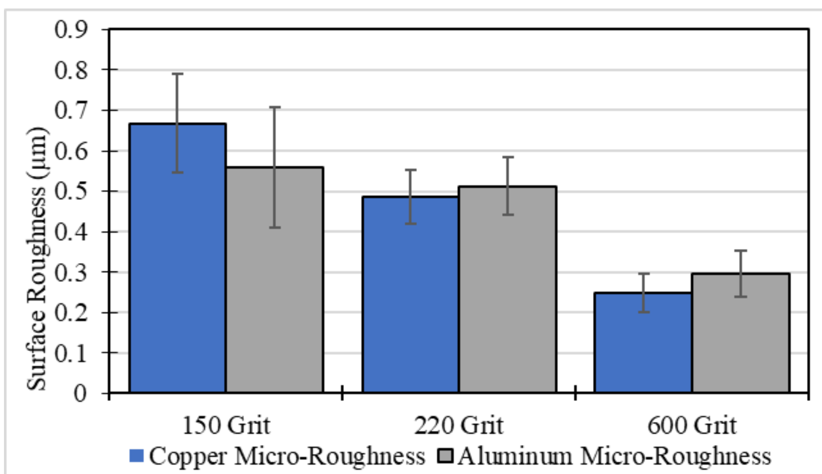

Figure 5: Histogram of Average Surface Micro-Roughness forEach Metal Sample

The micro-roughness decreases as the grit number increases, like the trend found with conventional roughness readings. Conventional Ra and micro-roughness readings often exhibit an inverse relationship. Micro-roughness measures small levels of surface irregularities, whereas Ra captures large scale surface variation.[5] Both Cu and Al tend to have fold over and smear incidents when undergoing a sanding operation. This, along with the decreasing grit particle size explains the decreasing Ra trend observed. On the other hand, on the micro-scale, increased amounts of peaks and valleys should be observed at higher grit levels, which should be captured by the micro-roughness. These peaks and valleys will increase the effective TIM bond area and should correlate to increased bond strength. Visual comparison of surface profile traces, as shown in Figure 6, showed that higher grit sandpaper created surfaces with a higher number of peaks and valleys that could not be represented with standard ISO Ra parameters. Since these measurements did not properly reflect the observed surface micro-roughness, it was necessary to explore alternative micro-roughness measurement parameters.

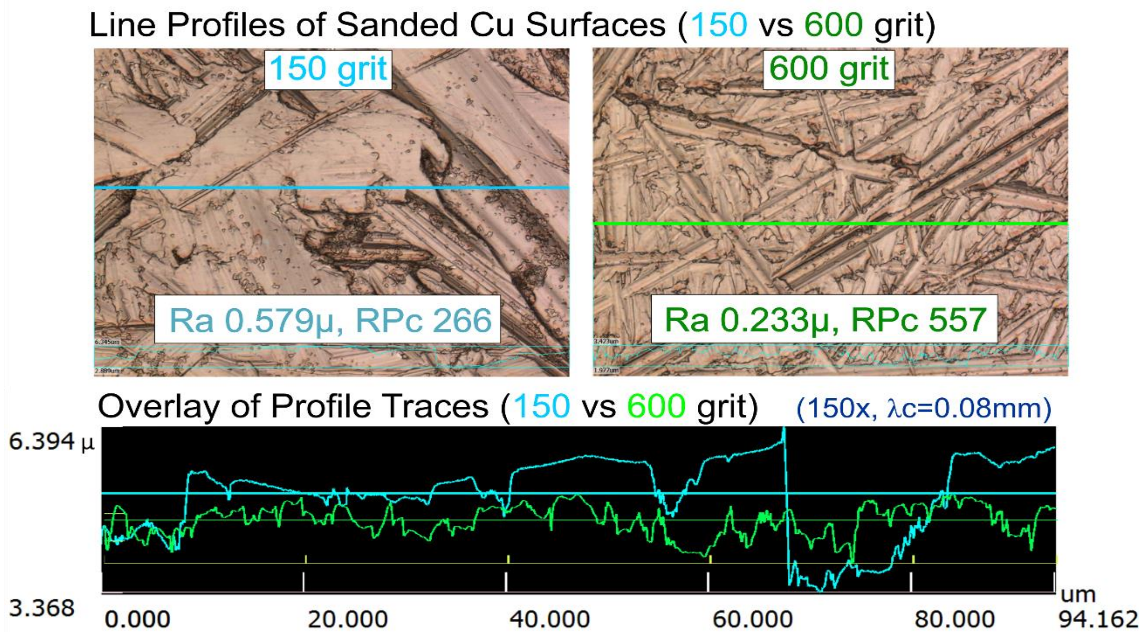

Figure 6: Line Profiles (150x Magnification)Showing Higher Number of Peaks and Valleys with Higher Grit Number

c. Peak Count

Standardized number of peaks (RPc) is another roughness parameter that can be used to characterize the micro-roughness. The RPc parameter is defined as the number of roughness profile peaks that cross a specified upper limit per measurement length selected.[6] Therefore, RPc values are sometimes reported as RPc/cm to represent the designated unit length. RPc was measured on representative samples at each grit level at a magnification of 150x with measurement length segments taken vertically and horizontally. The average RPc values by grit number are shown below in Figure7.

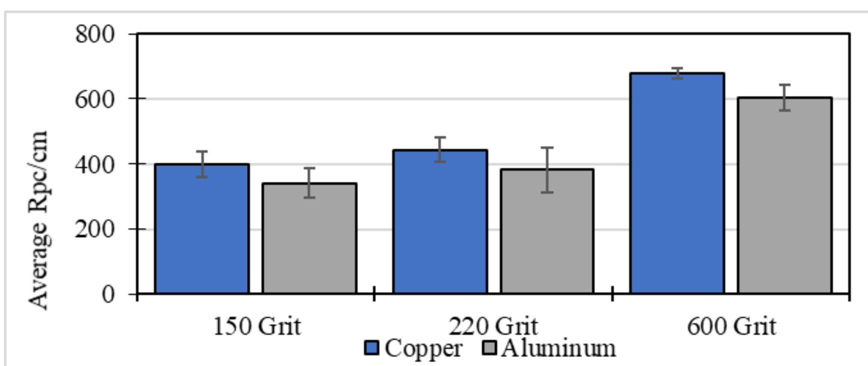

Figure 7: Histogram of Average Peak Count for Each Metal Sample

The RPc data produces an adequate representation of the surface micro-roughness. It shows the expected ranking of grit finishes and the micro-roughness increases with increasing grit level.

In conjunction with using the standard parameters to quantitatively measure surface roughness, the samples were also analyzed to qualitatively understand the relationship between grit level and surface condition.

d. Scanning Electron Microscopy Qualitative Analysis

Scanning electron microscopy was utilized to qualitatively evaluate the grit level surface finishes. The images presented below in Figures8and 9are at 1000x magnification.

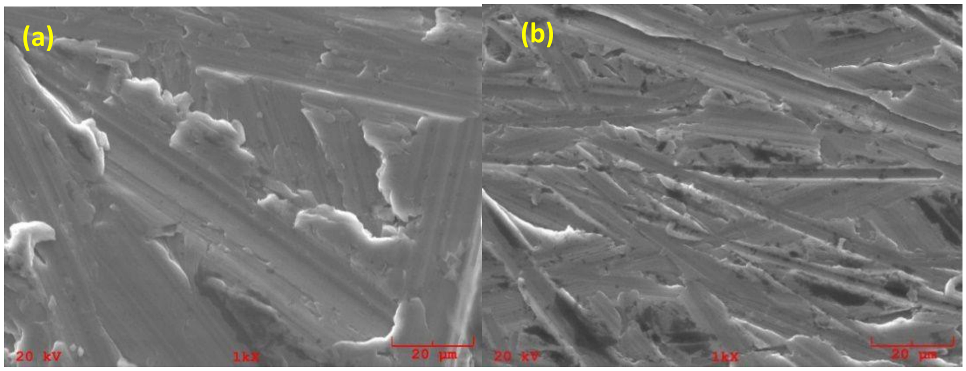

Figure 8:SEM Images of (a) 150 Grit Aluminum and (b) 600 Grit Aluminum

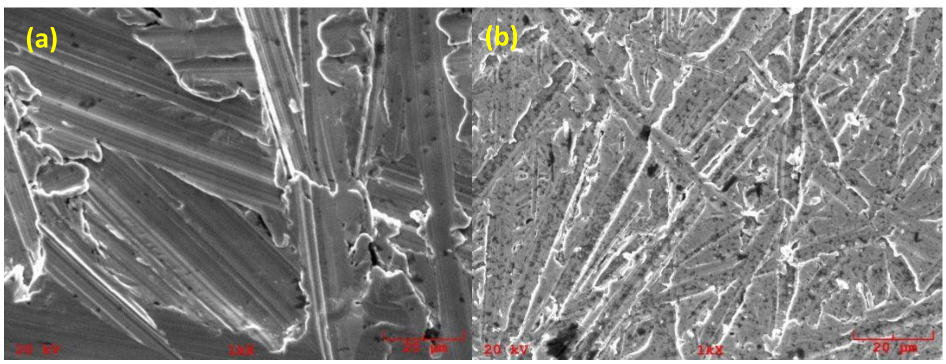

Figure 9: SEM Images of (a) 150 Grit Copper and (b) 600 Grit Copper

The SEM topographical images show the same results as the RPc data. Qualitatively, the 150 grit samples are smoother than the 600 grit samples. The surface topography of the 220 grit samples would fall somewhere in between the visualizations presented above. Furthermore, the Cu samples are coarser than the respective Al samples. This can be attributed to copper's increased tendency to fold over and smear when compared to Al.

e. Comparison to Heatsink Surface Finishes

The above surface evaluations were applied to current heatsink surface finishes. Four different Cu heatsinks were evaluated to further the investigation of surface finish on resulting TIM bond strength. Samples 1 and 2 were selected from product vintages with excellent historical performance. Sample 3 is another heatsink with typical machined finish, with good performance. Sample 4 was from a vintage with bond integrity issues noted. The heatsinks are detailed below, in Table3, with the poor performing vintage highlighted in red.

Table 3: Description of Heatsink Surface Finishes for Comparison to Grit Finished Samples Used in This Study

Heatsink	Description
Sample 1	Optimized/Target Surface Finish
Sample 2	Current Surface Preparation Process
Sample 3	Typical Machined Finish
Sample 4	Defective Surface Finish

The Ra and RPc data for the four heatsink samples are compared to the average Cu values obtained from sanding with three grit levels in Figures 10and 11below.

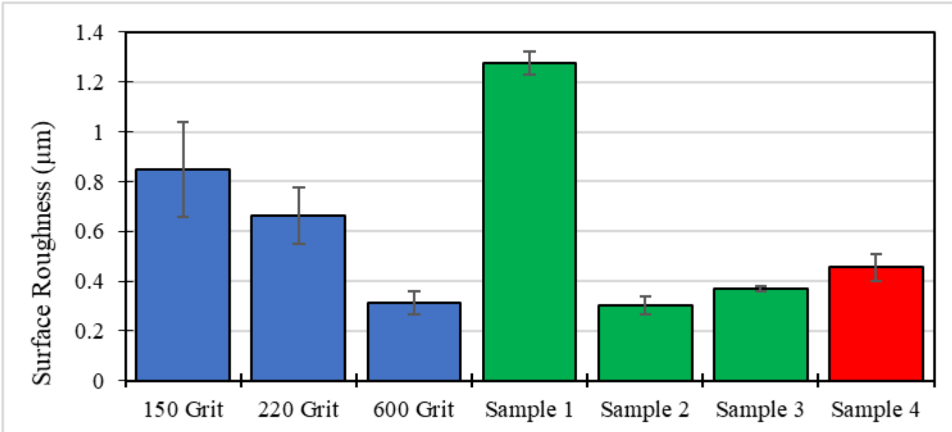

Figure 10: Histogram Comparing Surface Roughness between Each Grit Level and the Heatsink Samples

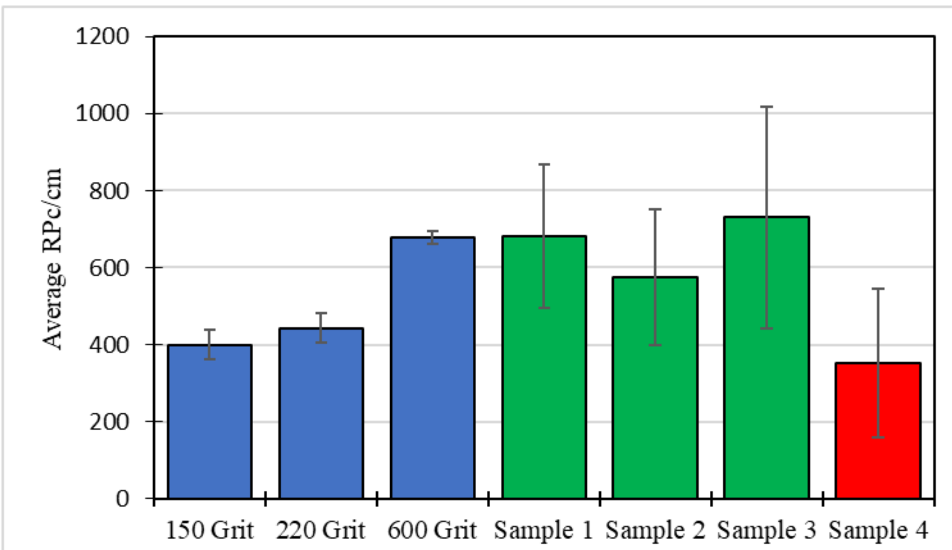

Figure 11: Histogram Comparing RPc of Each Grit Level with the Heatsink Surface Finishes

Sample 1, the target surface finish, yielded the largest surface roughness and one of highest peak counts. In contrast, the known defective surface finish measured the lowest peak count, with a generally low surface roughness. These results were expected because RPc represents the effective bond area. Interestingly, samples 1 and 4 do not show the same inverse relationship between Ra and RPc as observed between the other samples. The SEM investigation presented below in Figure12will provide more insight into the topographical differences.

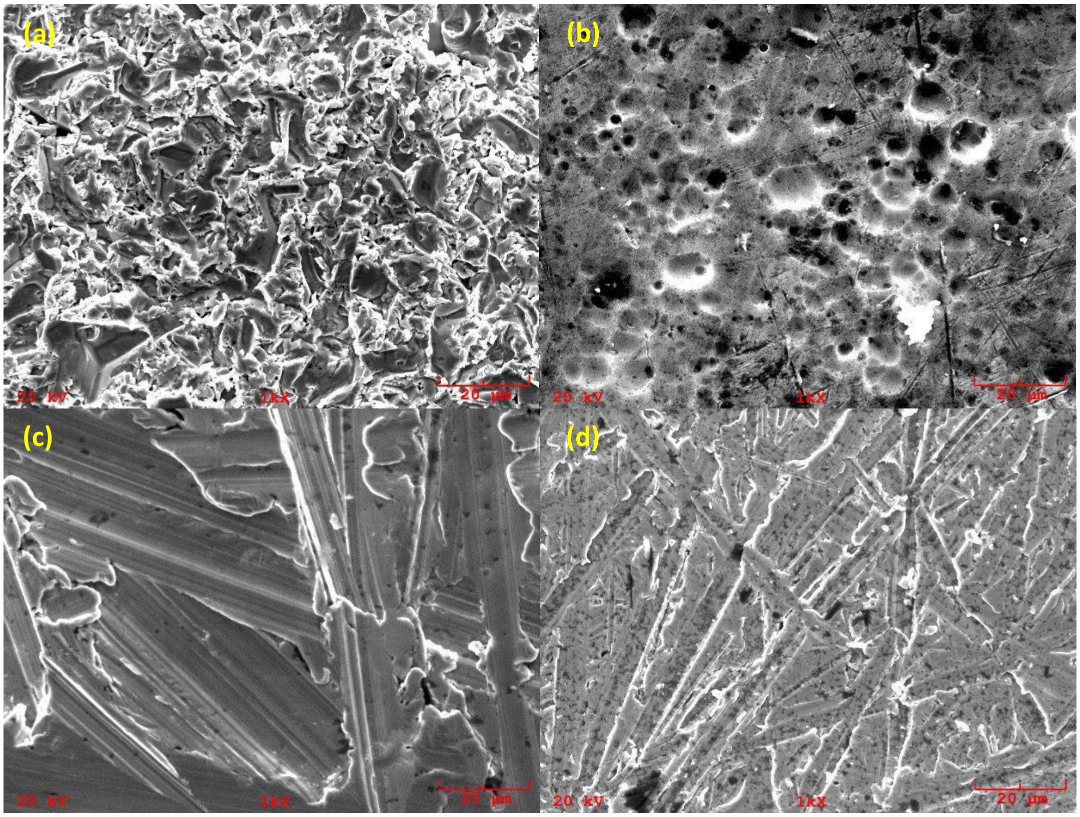

Figure 12: SEM Images at1000x Magnification of (a) Heatsink Sample 1 (b) Heatsink Sample 4 (c) 150 Grit Cu Sample (d) 600 Grit Cu Sample

The above figure compares the optimized and defective heatsink finishes with the 150 and 600 grit levels. Figure12(a)shows the surface with the most peaks and valleys, which produces the highest RPc and effective bond area. Figure 12(b)depicts a relatively flat surface with very few valleys and no discernible peaks. This results in a very small effective bond area, producing a weak adhesively bonded joint. Thus, sample 4 is confirmed to be a deficient surface finish. In comparison to the 150 and 600 grit samples that had abraded surfaces, the surface of sample 1 is covered with dimples. Surface dimples and bumps facilitate adhesive joining because they act as passive suction devices.[2] An abraded surface, as seen in the 150 and 600 grit samples, has a superior adhesion performance when compared to untextured surfaces. However, without the additional suctioning provided by the dimple morphology, these samples exhibit an effective bond area that is similar to sample 1, but not quite as high.

IV. Method of TIM Application / Cure and Resulting Bond Thickness

Before application of the TIM, the sample pair of blocks were placed on top of each other on a coordinate measurement machine (CMM), where a 4 X 4 grid of height measurements was taken off the top block. This provided a baseline thickness before TIM application. The TIM material was applied using an alignment fixture to position a 12 mil thick stencil over the Cu block. The Al block was placed onto the Cu block in a cure fixture, with a 1kg block used to compress the TIM. The samples were cured in the fixture to the designated time, and the thickness was re-measured on the CMM after cooling. The differential height before versus after cure was used to calculate the TIM thickness. Table 4 provides a summary of the bond measurements statistics.

Table 4: Statistics on TIM Bond Thicknesses

Average(mm)	0.0453
Standard Deviation (mm)	0.0376
Minimum Thickness (mm)	0.0199
Maximum Thickness (mm)	0.1656

V. Bond Strength Measurements

The silicone TIM bond strength was quantified by measuring the shear pressure using a mechanical testing system. This was done to determine which cure time and temperature combination yielded the proper bond strength for PCBA processing while also investigating which parameters had the greatest effect on final pressure. A summary of the shear pressure results, categorized by each grit level, is presented below in Table 5.

Table 5: Average Bond Strength Measurement

Sample Group	Average Shear Pressure (PSI)
150 Grit	366.75
220 Grit	391.49
600 Grit	484.96
Global	415.33

The average shear pressure and resulting bond strength increased with increasing grit level. This result was contradictory to what was hypothesized because 600 grit sandpaper is claimed to create a super fine macro surface finish, not adequate for adhesive bonding. Therefore, these results indicate the notable effect of micro-roughness on shear pressure.

a. Separation Mode

After the silicone TIM bond strength was measured, the adhered surfaces were analyzed to understand the relationship between separation mode and metal surface properties. All the samples exhibited near surface cohesive separation; the joint separated in the bulk silicone TIM which constitutes the adhesive, near the Cu or Al interface. Cognitive analysis tools were used to determine which factors had a significant effect on the TIM separation mode. It was determined that grit, Al roughness, and Cu roughness all had a substantial effect on the separation mode. As the grit level transitioned from a coarse to a smooth finish, the TIM separation mode converted from separation near the Al to separation near the Cu. At higher grit levels, and smoother finish, the Cu samples displayed more smearing and folding over. Therefore, the silicone TIM bond was not adhered to the primary surface, and near surface cohesive separation occurred adjacent to the Cu interface. Subsequently, as Cu and Al roughness increased, the samples tended to separate more towards the Al side.

VI. Thermal Bond Parameters Effect on Resulting Bond Strength

A combination of statistical and cognitive analytic tools, analysis of variance (ANOVA) statistical model and a cognitive key driver analysis tool, were used to determine which parameter (surface roughness, grit, cure temperature, and cure time) had the greatest effect on the resulting TIM bond strength. The key driver tool provided the predictive strength of a given element which expresses its importance in relation to the factor’s ability to drive the outcome. The higher the predictive strength, the stronger it is correlated with the final outcome. The ANOVA p-values and predictive strength values are presented below in Table 6. A p-value less than 0.05 and a predictive strength above 25% indicates that factor had a significant effect on resulting bond strength, as indicated by the green text.

Table 6: ANOVA P-Values and Cognitive Predictive Strength Values for the Different Experimental Factors

Factor	P-Value	Predictive Strength
Cure Temperature	0.0693	28%
Cure Time	0.2488	
Cure Time x Temperature Interaction	0.9699	
Grit	0.00	31%
Copper Roughness		35%
Aluminum Roughness		25%

Based on ANOVA analysis, the cure time and the interaction between cure time and cure temperature were found to have no significant effect on the final outcome. Through plotting the one-factor analysis of the ANOVA with shear pressure bond strength as a function of cure time, a general pattern emerges with the bond strength increasing with greater cure time. This plot is shown in Figure 13 below. It should be noted that the cure time was always greater than the minimum vendor recommended cure time for silicone TIM, which is likely why this parameter was less significant.

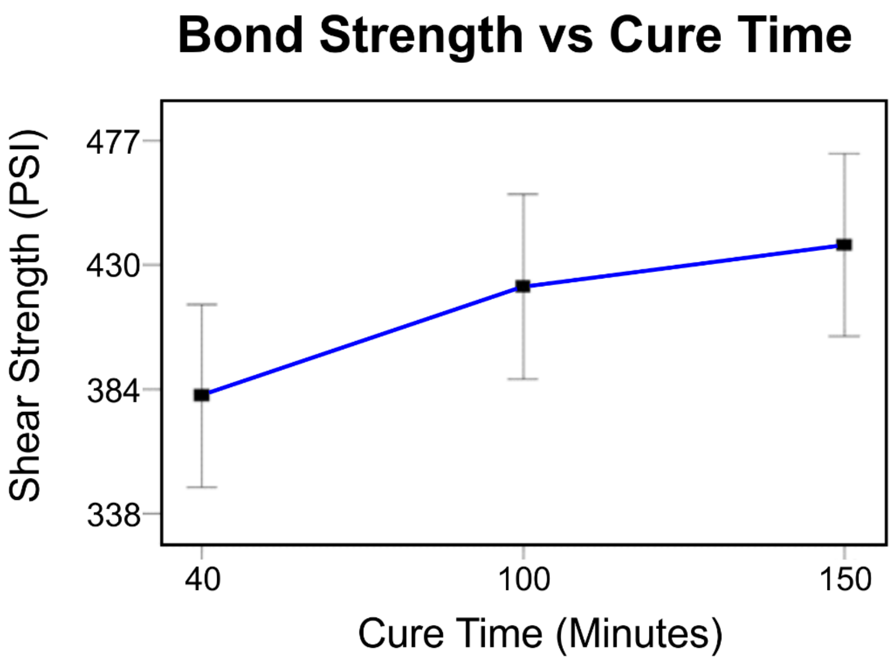

Figure 13: Bond Strength as a Function of Cure Time

Cure temperature was shown to be more significant than cure time. As shown in table 6, a p-value of 0.0693 would deem this factor marginally significant but a predictive strength of 28% indicates that cure temperature does indeed have a significant effect on resulting bond strength. When plotting the one-factor ANOVA analysis with shear pressure bond strength as a function of cure temperature, the bond strength increases with greater cure temperature. These results are displayed in Figure 14. Table 7also presents a summary of the statistics of shear pressure bond strength as function of cure time and cure temperature.

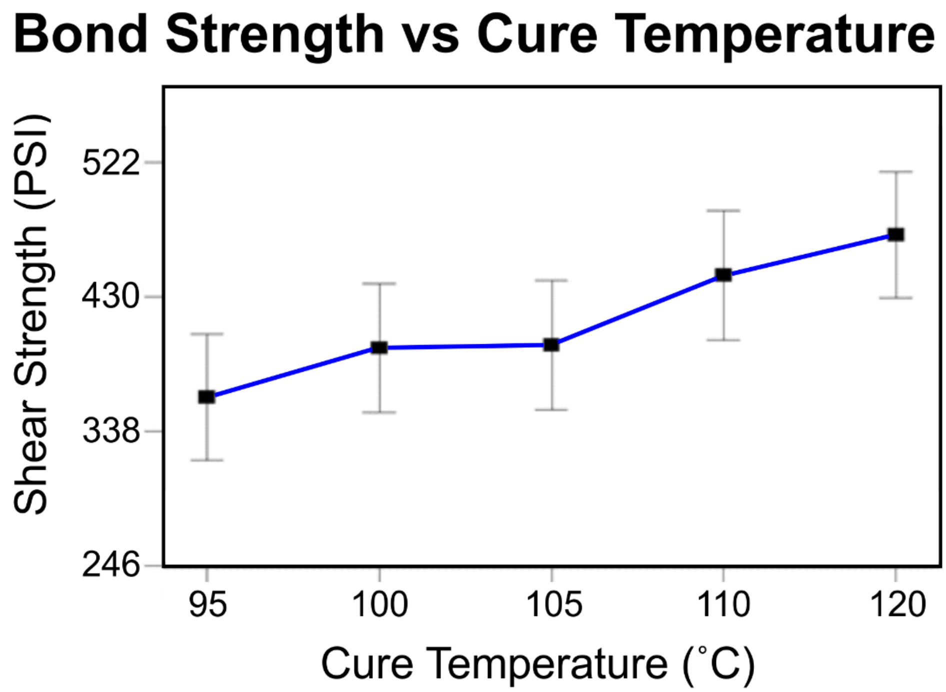

Figure 14: Bond Strength as a Function of Cure Temperature

Table 7: Statistics on Bond Strength as a Function of Cure Temperature and Cure Time.

Cure Temperature Statistics of Response Shear Pressure				
Cure Temp (Deg)	Average (PSI)	Standard Deviation (PSI)	Min (PSI)	Max (PSI)
95	367.338	97.173	250.681	504.399
100	394.816	89.542	284.567	567.249
105	396.780	61.196	316.882	500.453
110	444.626	86.053	306.896	559.951
120	471.331	98.967	357.338	614.927
Cure Time Statistics of Response Shear Pressure				
Cure Time (min)	Average (PSI)	Standard Deviation (PSI)	Min (PSI)	Max (PSI)
40.000	391.850	92.946	281.648	593.817
100.000	422.247	100.240	256.317	567.249
150.000	432.718	88.751	250.681	614.927

a. Interaction of Roughness and Cure Temperature

From the ANOVA and predictive cognitive analysis tools, surface finish was found to have the greatest effect on the shear pressure response. Grit number was found to be the factor having the most significant effect on the final result. As the grit number used to prepare the samples increased, the resulting shear strength increased. This relationship is illustrated by the main effects plot in Figure 15 below.

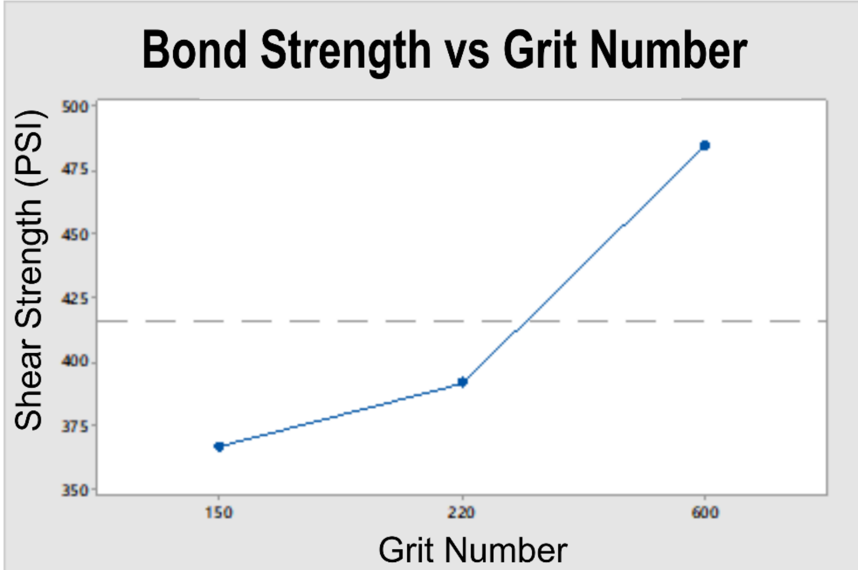

Figure 15: Bond Strength as Function of Grit

As the Cu and Al mean surface roughness decreased, the final bond strength increased. These results were expected because grit level is inversely proportional to mean surface roughness. The correlation between micro-roughness, peak count, and pressure was explored using a heat map cognitive analysis tool, presented below in Figure 16.

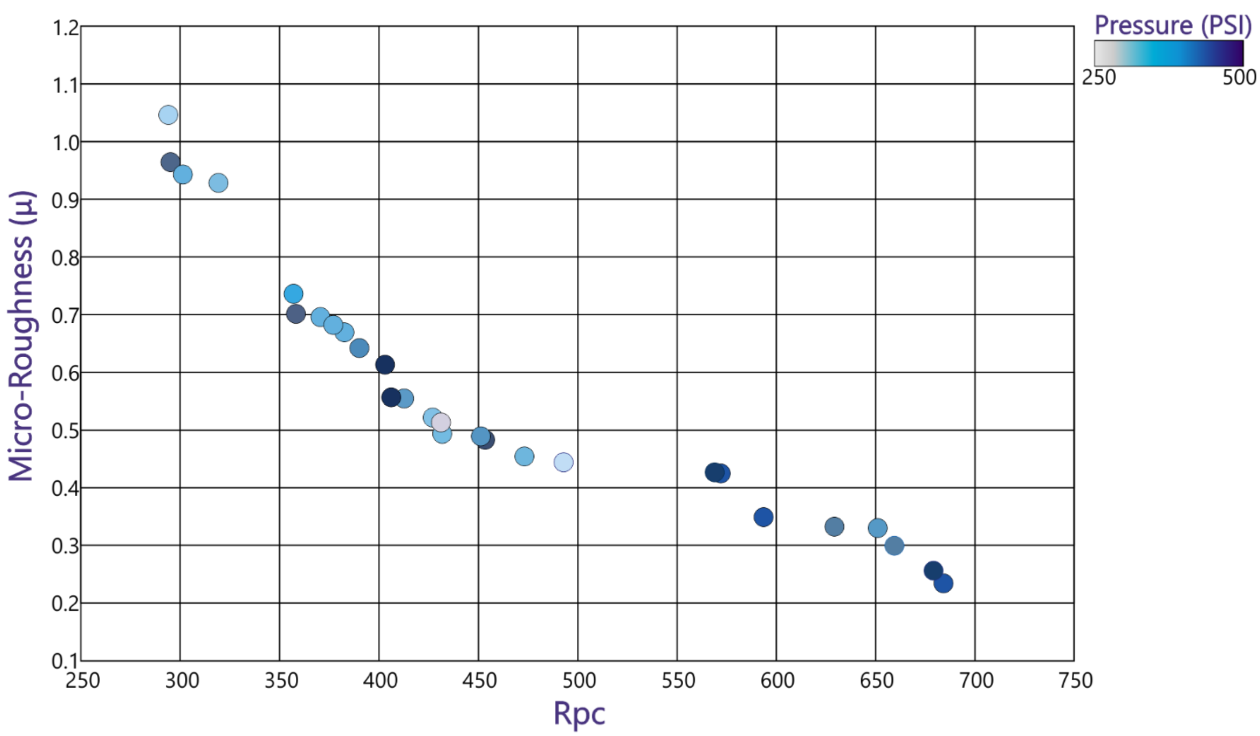

Figure 16: Pressure as a Function of Micro-Roughness and Peak Count

The color intensity in the above visualization is used to represent increasing pressure as a function of micro-roughness and RPc. In general, as the micro-roughness decreased and the peak count increased, the resulting shear pressure increased. Lastly, the interaction between surface micro-roughness and cure temperature was evaluated. The results are presented below, in Figure 17.

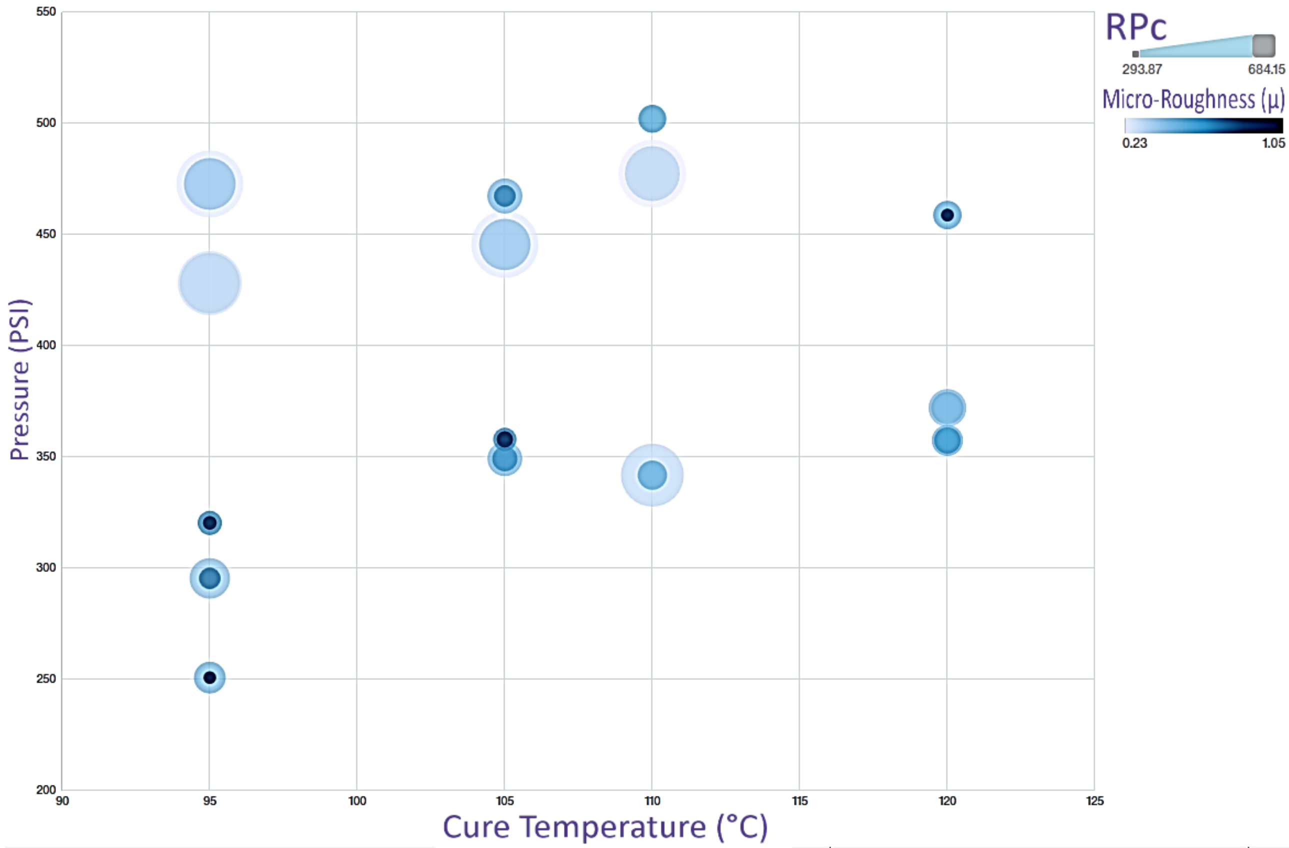

Figure 17: Interaction between Roughness and Cure Temperature

The size visualization above represents increasing RPc, while the color intensity represents increasing micro-roughness. The 95°C cure samples have the highest sensitivity to both RPc and micro-roughness conditions. This is consistent with observed historical product performance, where lower temperature cure has been found to be more sensitive to surface condition variation than the higher temperature cure process. High RPc values achieved high bond strength even at the lowest cure temperature.

VII. Discussion

Historical data from failure analysis of deficient heatsink bonds has consistently found that low roughness readings are correlated with increasing likelihood of failure and weak adhesively bonded joints. The results of this study are at first glance not consistent with the historical failure observations, and in fact show the opposite trend. This inverse relationship between roughness and adhesion has been reported elsewhere.[3] Mechanical adhesion theory would predict that rougher surfaces would generally provide more interfacial surface area and provide some degree of mechanical interlocking that would not be present on smooth surfaces. However, surfaces that are coarsely ground may exhibit more surface flaws (fold-over, smear) than finer finishes, and may sometimes exhibit poorer wetting of adhesive. The samples evaluated in this work were not likely influenced by surface flaws or wetting, but more by the presence of microscopic asperities on the surfaces that appeared to be smoother finishes. It was demonstrated that the high grit number finishes had significantly higher numbers of mechanical interlocking sites when measured using appropriate metrics (RPc). This illustrates the importance of micro-roughness as a primary control measurement for critical bond surfaces. The sanding method used in this experiment is not typically used in volume production processes. Volume production will typically use fly cutting or other similar machining methods. These production machining methods will produce surfaces that will have more periodic shape artifacts (waviness) which will require the appropriate cutoff filter to be applied. Production machining processes often use a chemical polishing to remove residues after the machining operation. This may explain the observed smooth surfaces found on historical failure analysis results reported above. Note that heatsinks with deficient bond strength from historical performance typically were found to have extremely low micro-roughness (< 100 µ), which is well below the lowest micro-roughness evaluated in this DOE (> 200 µ).It is recommended that micro-roughness parameters (both minimum cutoff / high magnification Ra and RPc) be used to supplement conventional roughness range specifications for control of bond integrity.

VIII. Conclusions

The experimental results from this work confirmed the influence of micro-roughness on mechanical bond performance of both Cu and Al material grades. Conventional Ra specifications were also demonstrated to be inadequate for control of bond strength consistency. Optimum bonding performance can be ensured through application of the RPc micro-roughness specification. If Ra is used to control micro-roughness, it should be measured with high magnification and use the minimum possible cutoff filter. Ra micro-roughness measured with minimum standard cutoff filter (0.08 mm) has provided correlation with bond performance at very low Ra levels, but RPc was demonstrated to achieve the best correlation with bond integrity across the range of surfaces in this DOE. Optimum bond strength was achieved with high cure temperature (120°C), longer cure times, and RPc above 500. This work also demonstrated that adequate bond strength can be achieved with the lower temperature cure condition, allowing usage for temperature sensitive components.

IX. References

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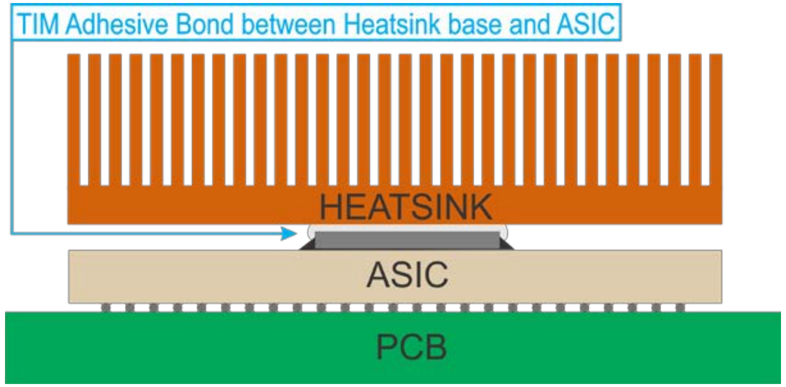
Outline

- Introduction
- Historical background on bonded heatsink performance
- Experimental Design:
  - *Heatsink bonding parameters / DOE*
  - *Surface characterization*
- Experimental Results
- Conclusions

Introduction

- Today's high performance servers have several cooling challenges
  - *Multiple power dissipating devices, densely packaged*
  - *Limited space for mechanical retention features → bonded heatsinks*
  - *Reliability in shipping / handling / and long term operation & power cycling*
- Adhesive TIM Options
  - *Acrylic → room temperature cure, but limited resilience / long term reliability*
  - *Silicone → thermal cure, excellent resilience and long term reliability*
  - *Epoxy → intermediate performance, not as robust as silicone*
- Illustration of bonded heatsink on ASIC:



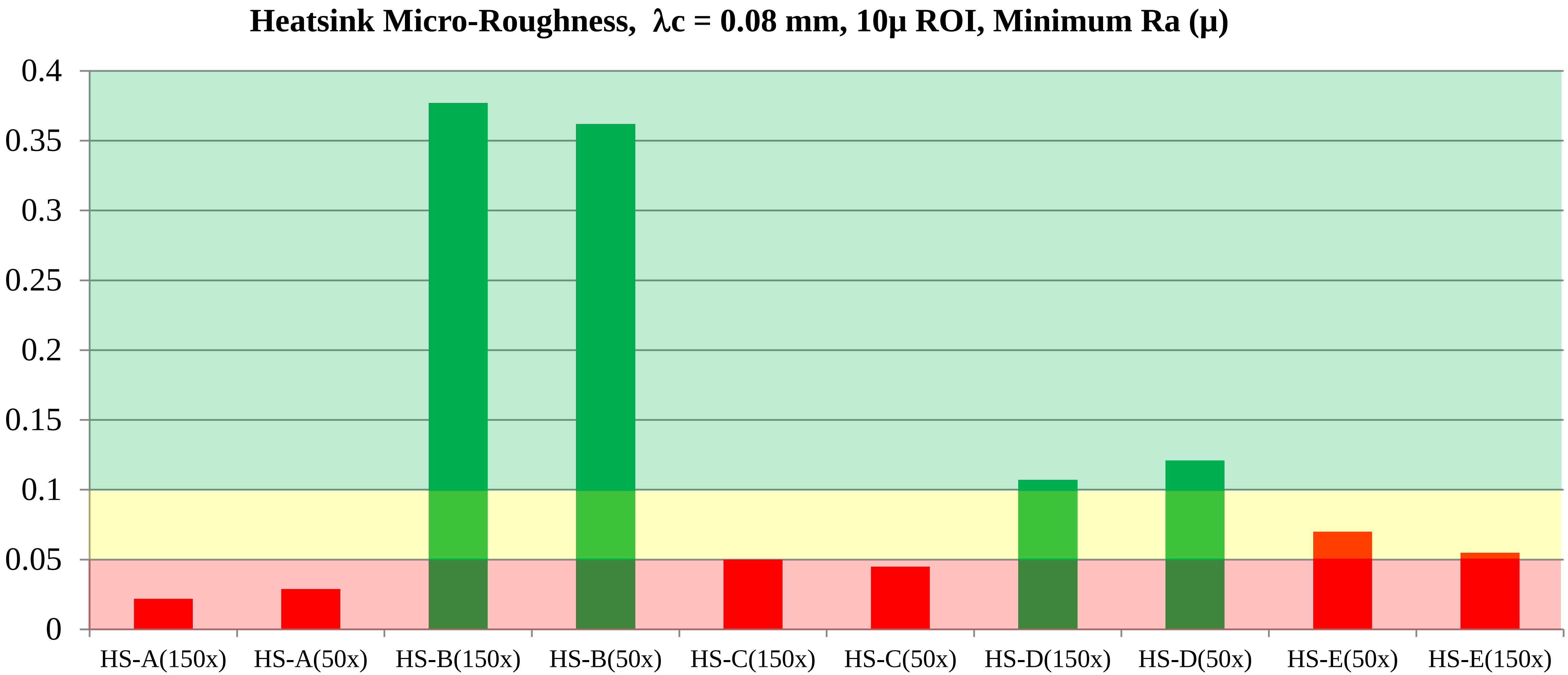
Introduction

- Challenges for heatsink bonding
  - *TIM material provides both thermal interface and mechanical retention*
  - *Control of surface conditions is critical to provide consistent bonding*
    - Roughness (the primary focus of this work)
    - Flatness and cleanliness are also critical parameters
- Challenges for thermally cured TIM adhesives
  - *Temperature Sensitive Component (TSC) devices with bake time / temperature limits will restrict bake conditions*
  - *LEDs, Fuses, Capacitors, Inductors, and other TSC components are commonly found on PCBs requiring bonded heatsinks*
- Bonding at lower temperature requires longer cycle time and may be more sensitive to minor surface deficiencies

Historical background on bonded heatsink performance

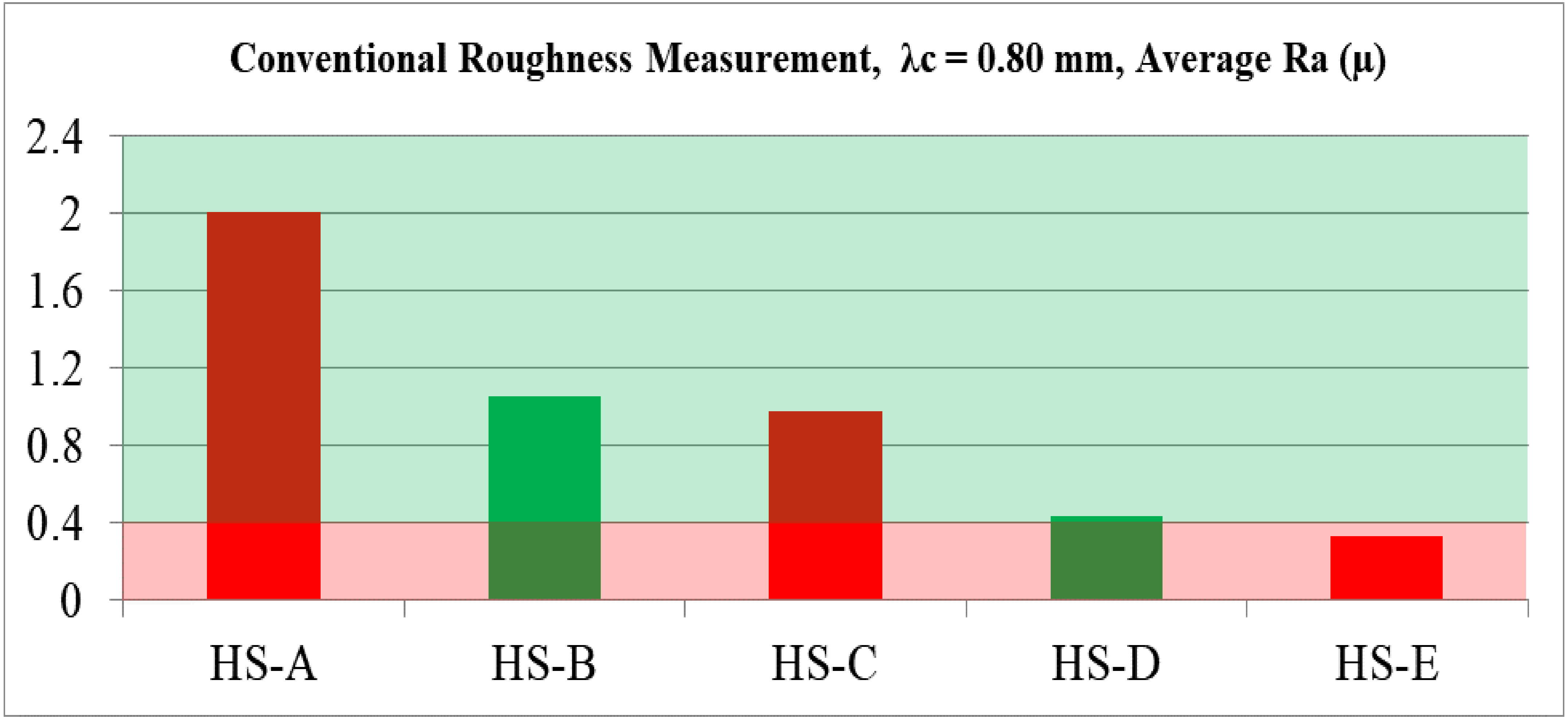
- Surface roughness has been identified as an important specification parameter
  - *First level roughness (Ra) range has been used for incoming material control*
  - *Typical print specifications include (Ra or associated ISO Number) without any further detail regarding cutoff filter or magnification used*
- Cumulative analysis of good performing heatsinks and other heatsinks with deficient bond performance has identified some common conditions
  - *Micro-roughness when measured with low cutoff filter and high optical magnification were found to correlate well with bond performance*
  - *Conventional macro-roughness without a specified cutoff filter (as typically included in part specifications) did not provide correlation to bond performance*
- The following charts show roughness characterization of 5 different heatsinks from suppliers A through E, illustrating the much stronger correlation between micro-roughness and mechanical performance

Historical background on bonded heatsink performance



Poor performing heatsinks (Red Bars) had micro-roughness between .02 and .08µ

Historical background on bonded heatsink performance



Conventional macro roughness showed no correlation between roughness and bond performance

Experimental Design: Heatsink bonding parameters

- Primary goal was to establish robust process limits including low temperature cure option
- Copper and Aluminum surfaces were chosen based on frequent use in product applications
- DOE Process variables:
  - *Surface Finish, established by sandpaper grits:*
    - *150 grit (ISO equivalent N6 to N7)*
    - *220 grit (ISO equivalent N3 to N5)*
    - *600 grit (ISO equivalent N1)*
  - *Cure Temperature (95, 100, 105, 110, and 120 °C)*
  - *Cure Time (40, 100, and 150 minutes)*

Roughness-ISO (Sandpaper Grit)	N1 (600 grit)	N3-N5 (220 grit)	N6-N7 (150 grit)	N1 (600 grit)	N3-N5 (220 grit)	N6-N7 (150 grit)	N1 (600 grit)	N3-N5 (220 grit)	N6-N7 (150 grit)
Cure Temperature (Deg C)	40 Minutes	40 Minutes	40 Minutes	100 Minutes	100 Minutes	100 Minutes	150 Minutes	150 Minutes	150 Minutes
95	1	1	1	1	1	1	2	1	2
100	1	1	1	1	1	1	1	1	1
105	1	1	1	1	1	1	1	1	1
110	1	1	1	1	1	1	1	1	1
120	2	1	2	1	1	1	1	1	1

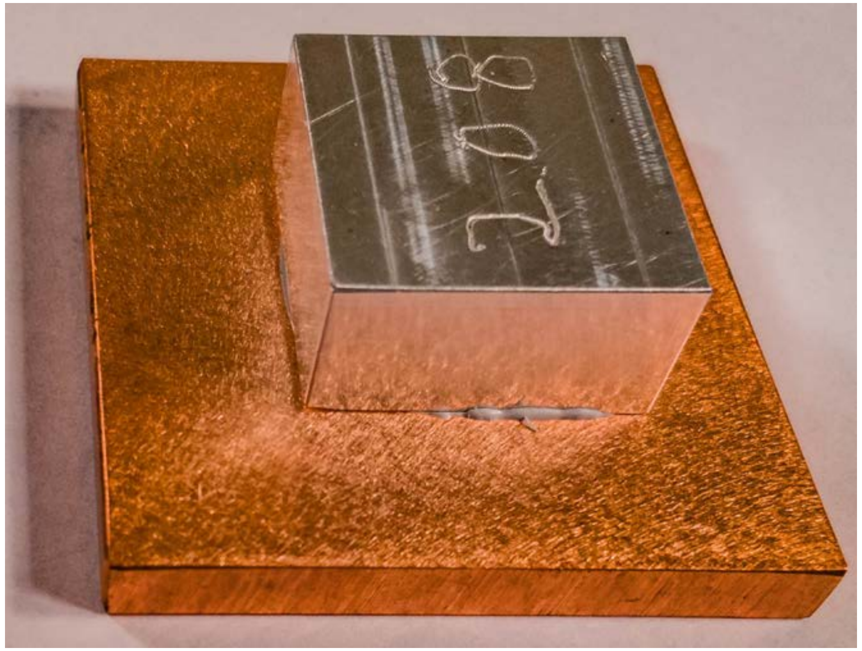
Experimental Design: Heatsink bonding parameters

- A Silicone TIM material was selected for this evaluation, with the following properties:

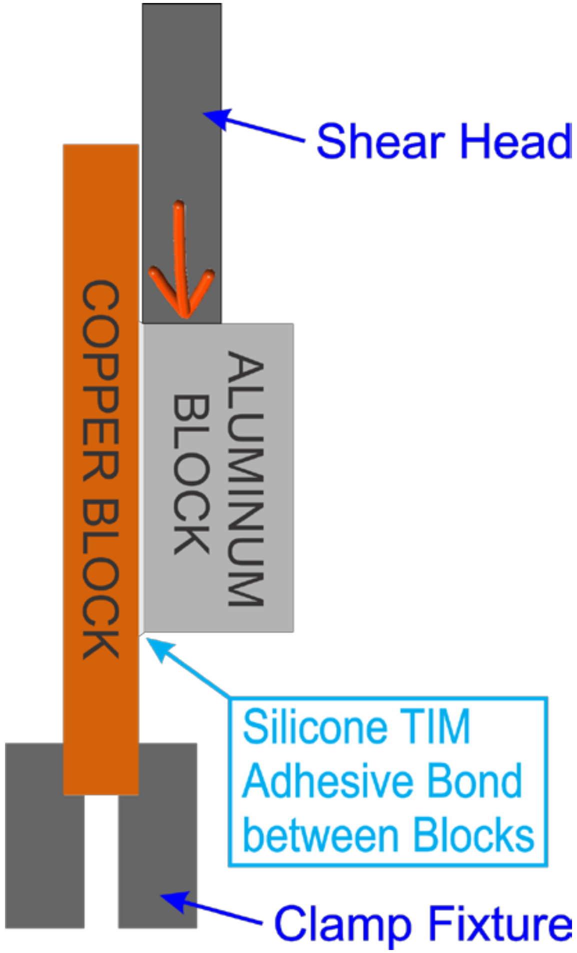
Property	Value
Adhesive Cure options	90 minutes at 100ºC 30 minutes at 125ºC
Operational Temperature Range	-45 to 200ºC
Unprimed Adhesion – Lap Shear (Al)	4.5 MPA

- Surface preparation:
  - *One copper and one aluminum block were finished with the same grit sandpaper*
  - *Block pairs were adhesively bonded per the DOE matrix prior to shear strength testing*
- Surface and characterization:
  - *Bond surfaces were characterized using a laser optical characterization tool*
    - Conventional Ra roughness was measured at 20x magnification
    - Micro-roughness was measured at 150x with minimum cutoff filter (0.08 mm)

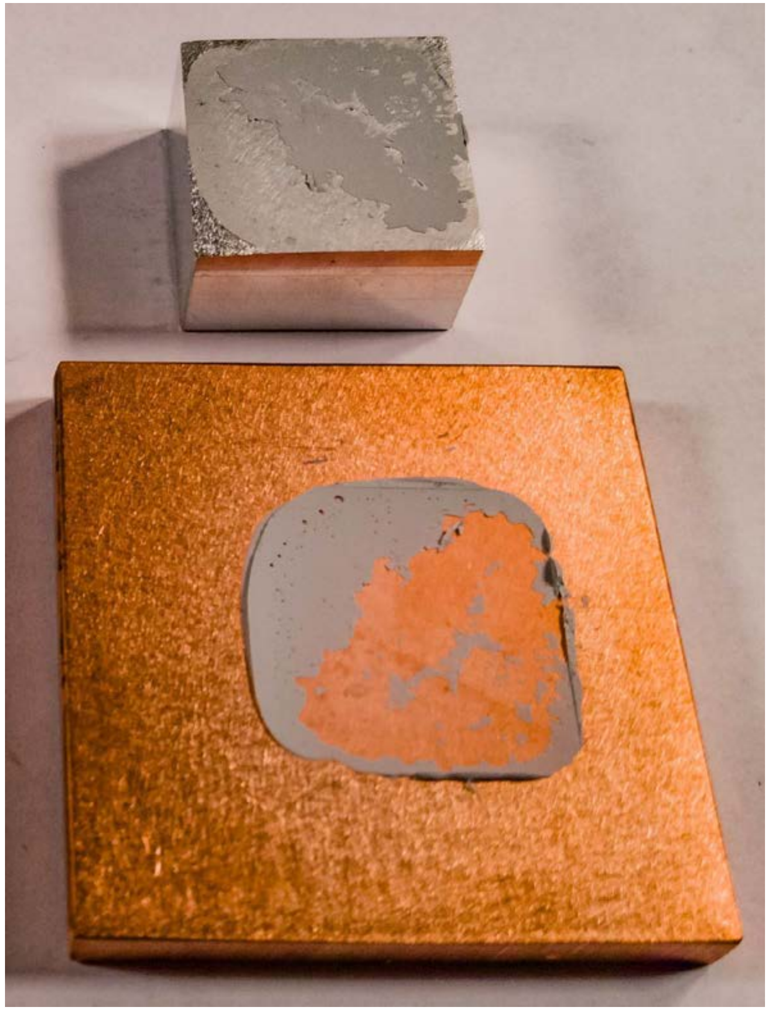
Photos of Cu / Al blocks as assembled and after shear test



Cu and Al Blocks as bonded



Shear test configuration



Cu and Al Blocks after shear

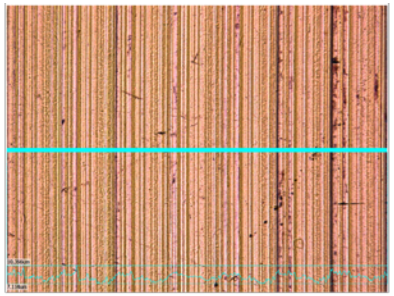
Experimental Design: Surface Characterization parameters

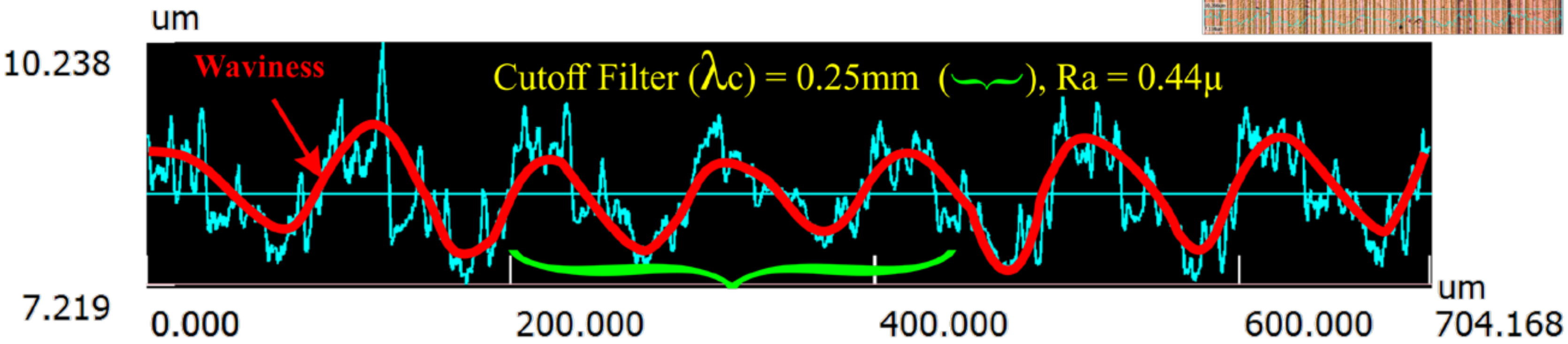
- All sample surfaces were measured for roughness (Ra) at 20x optical magnfication
- Additional measurements were made using a micro-roughness method using optimum parameters to detect finer surface features:
  - *50x to 150x optical magnification*
  - *Minimum length cutoff filter (λ_c) of 0.08 mm per ISO 4287-1997 standard*
- Micro-roughness using an alternative method (RPc) was also measured on a sample of finished blocks
  - *RPc was found to have the best correlation to bond integrity for the samples evaluated in this experiment*
- Illustrations of waviness filtering using cutoff filter (λ_c), and the use of RPc peak counts to assess micro-roughness are shown on the following pages

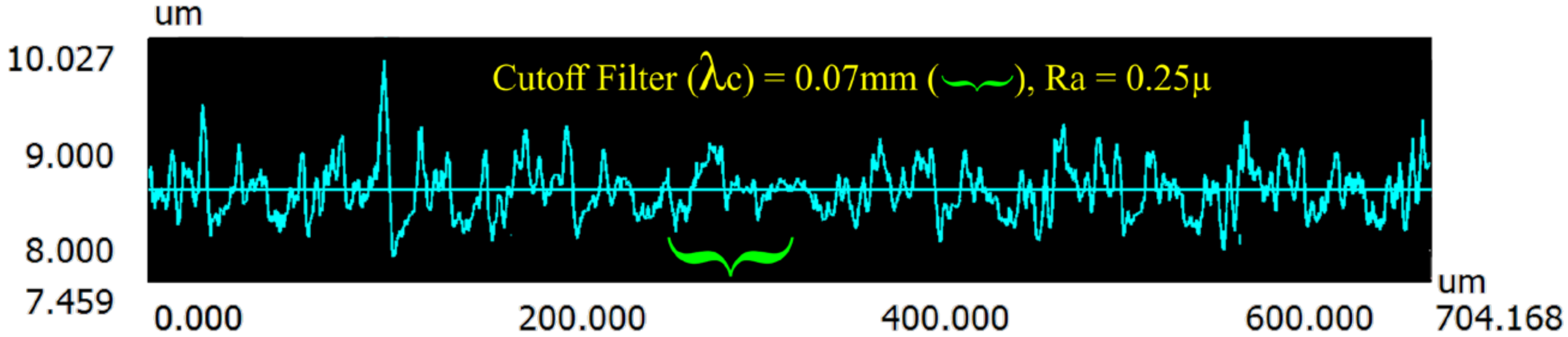
Waviness and Cutoff Filter (λc) Illustration (line profiles)

Waviness Illustration:

→Upper graph contains both Roughness and Waviness data
→Lower graph (Cutoff Filter applied) shows Roughness data
→Right image depicts profile across heatsink surface

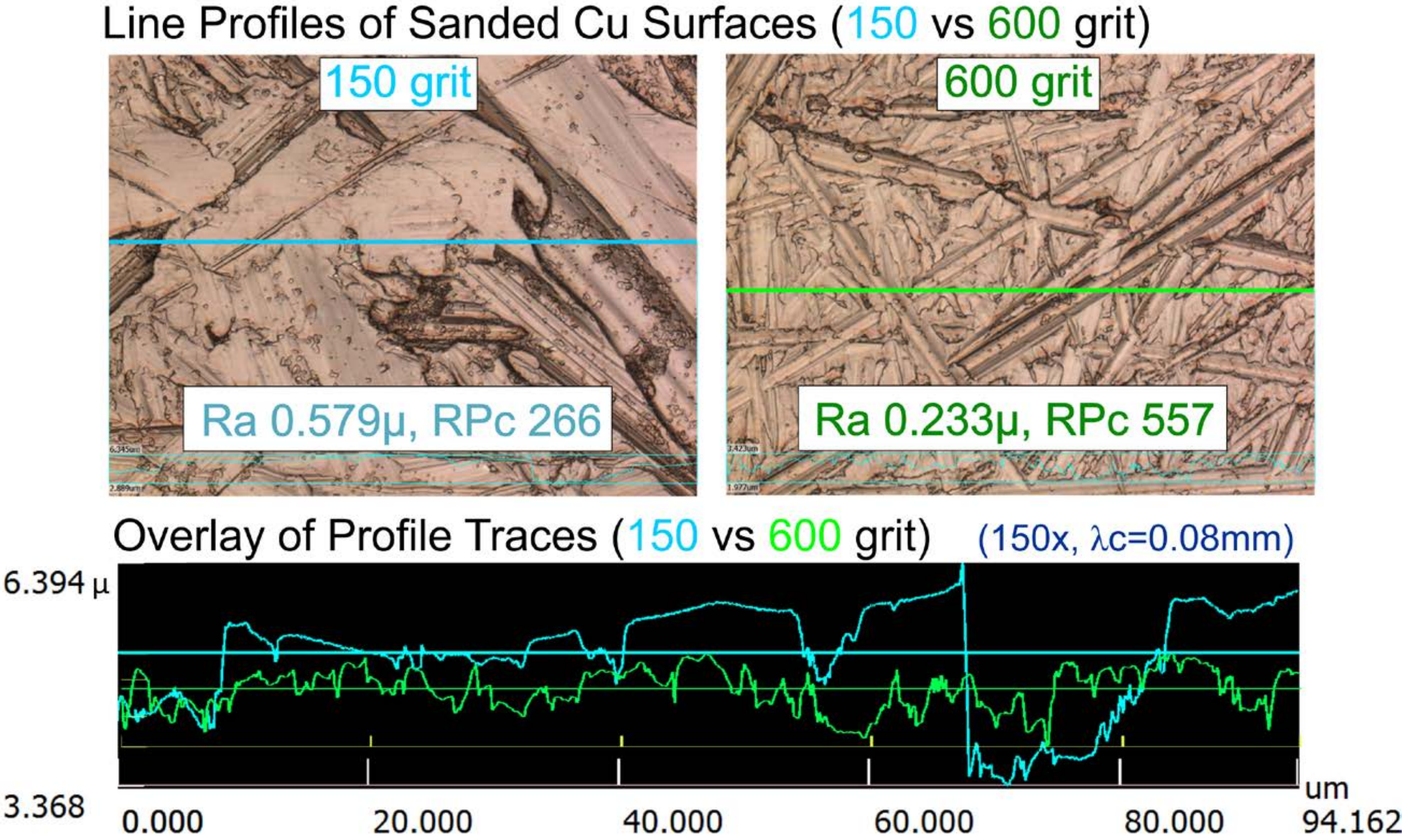






Top chart [λc = 0.25mm] has substantial waviness, Lower chart (λc = .07mm) shows roughness only

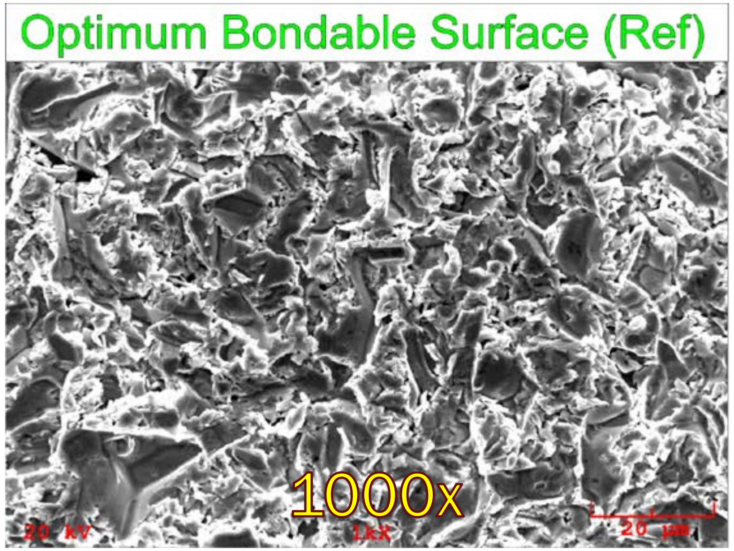
RPc comparison between course and fine sanded surfaces

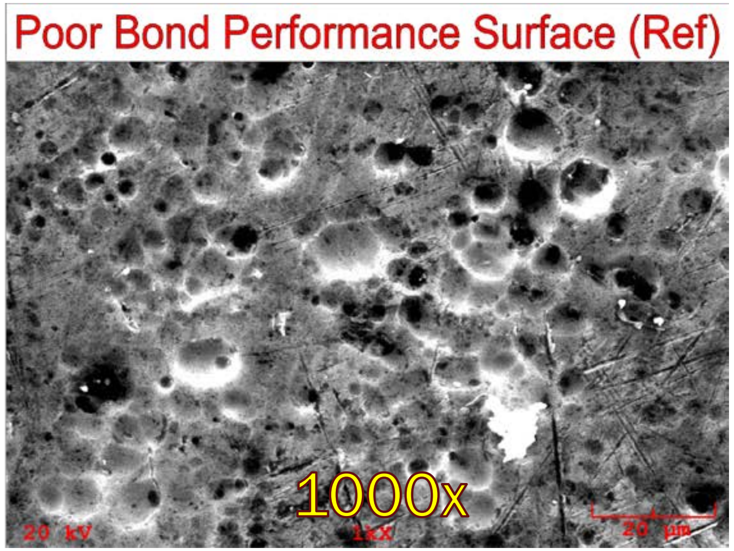


Course grit profile has higher Ra, but much lower RPc (peaks per cm) vs fine grit profile

Experimental Design: Surface Characterization with SEM

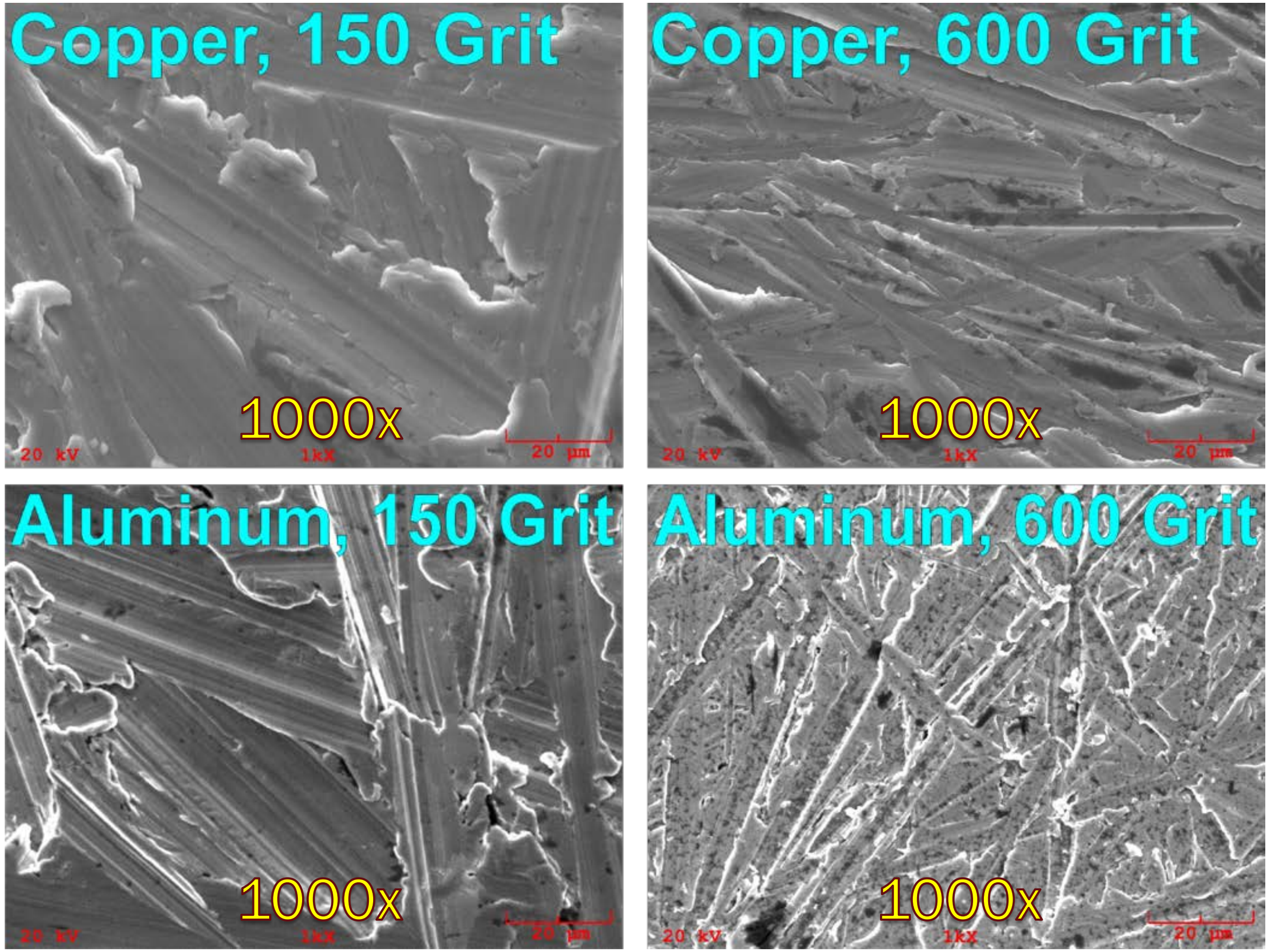
- SEM analysis was used to better understand the surface conditions created by the various grit sanding operations, as shown on the following page
- Additional SEM analysis was performed on some other reference heatsink surfaces for comparison as shown below





Deficient surface on right shows smoothed features at 1000x magnification (possibly due to chemical polish)

Experimental Design: Surface Characterization with SEM

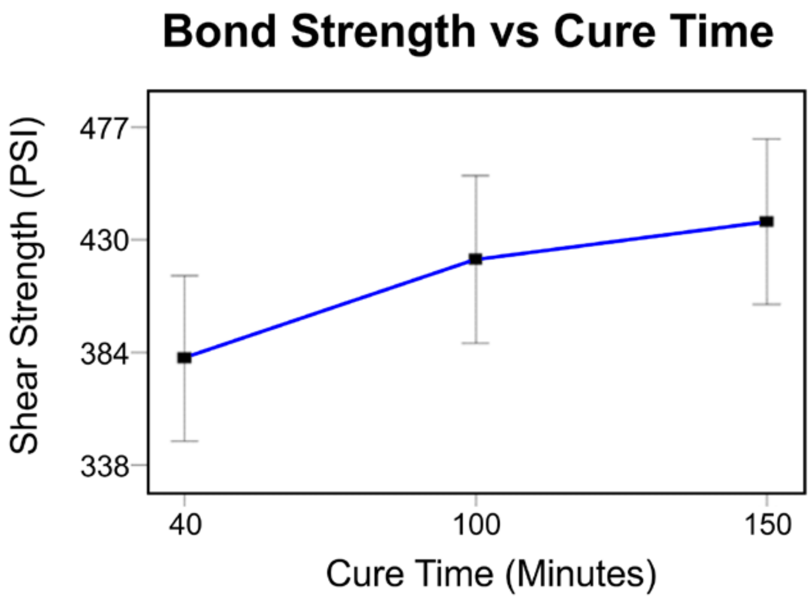


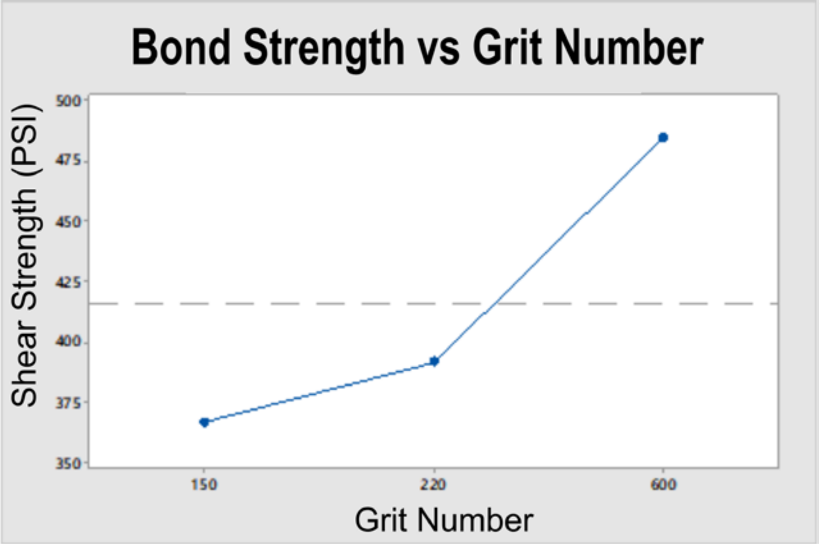
Courser grit shows large scale surface deformation, with higher smearing / fold-over

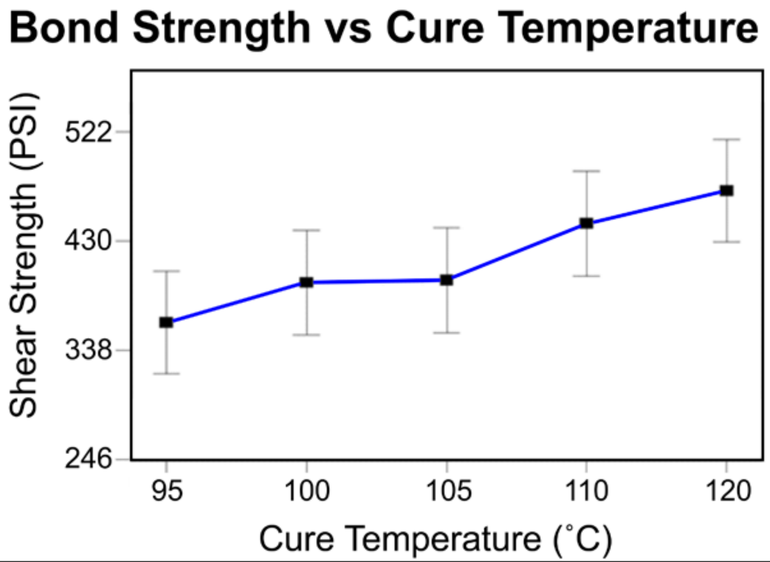
Experimental Results

- All samples were tested for shear strength
- Bond area was measured for each sample to enable calculation of ultimate shear strength
- Samples were inspected and characterized for separation mode
  - *Virtually all surfaces exhibited near-surface cohesive separation*
  - *Finer grit sanded surfaces had predominant separation near the copper surface*
    - *likely due to higher level of smearing / fold-over on copper sanded with this grit*
- Cognitive analysis tools, as well as conventional ANOVA statistics were used to evaluate significance of each of the DOE parameters and other measured attributes

Experimental Results

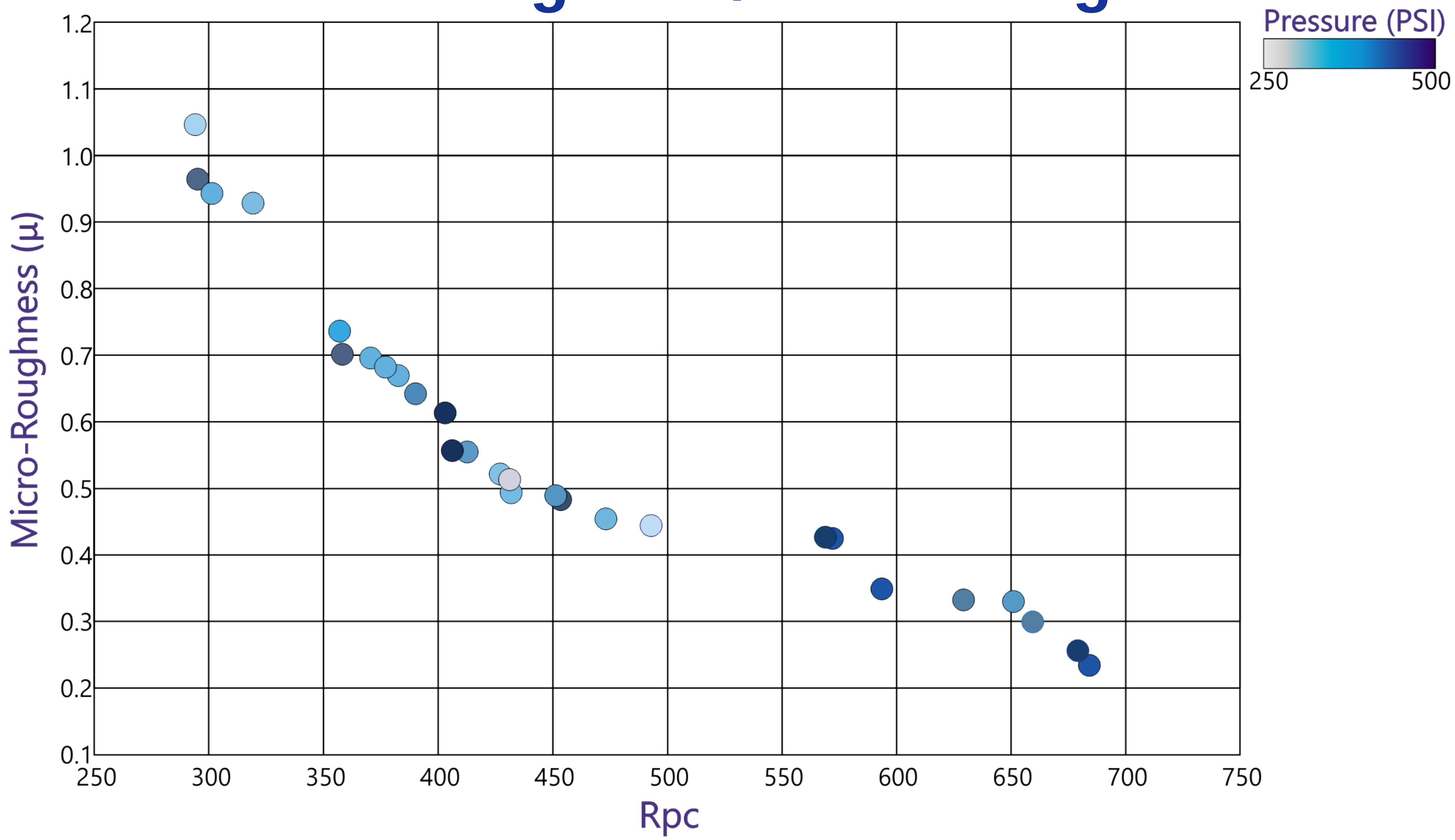






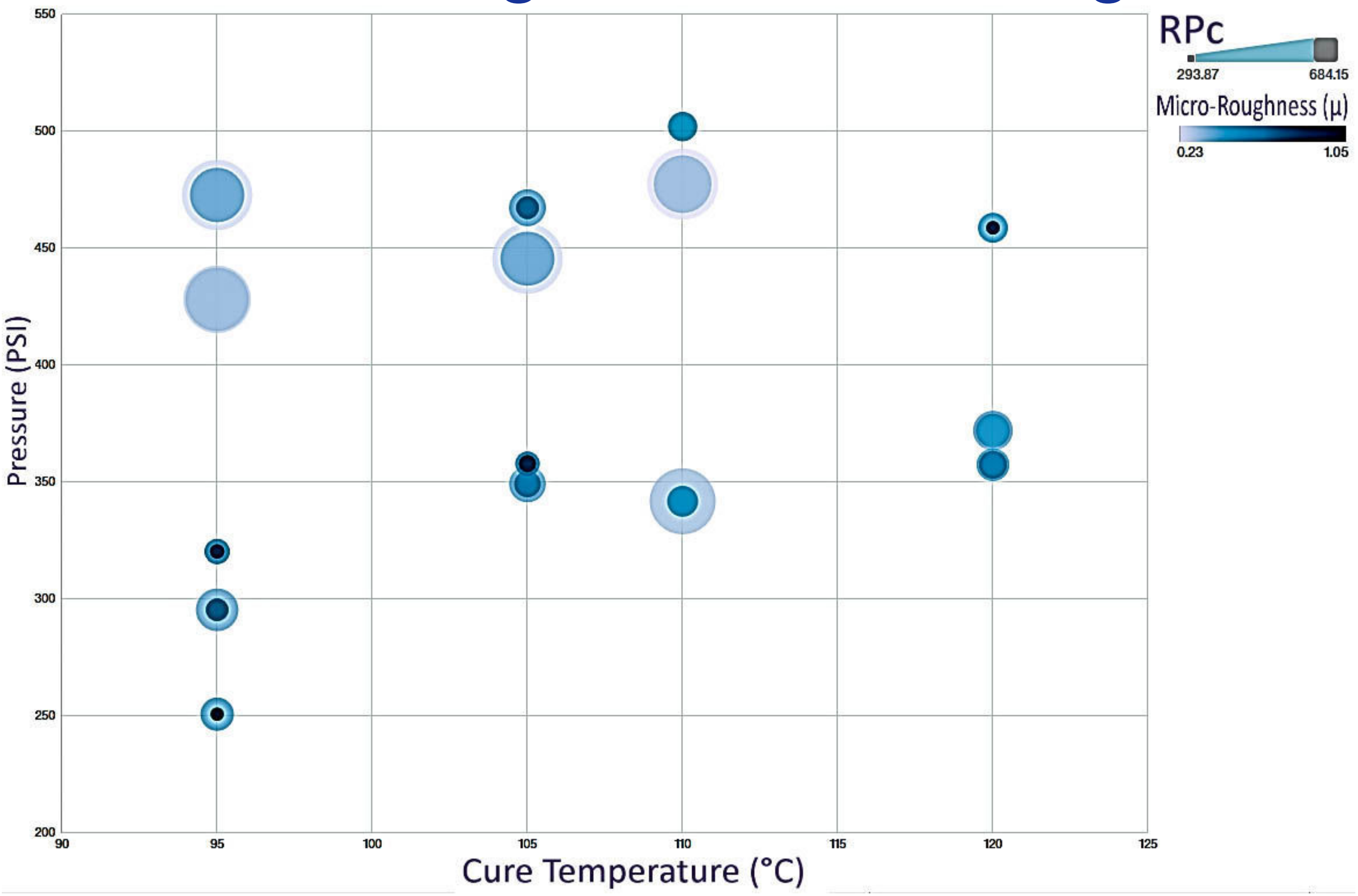
Higher grit number, higher cure temperature and higher cure time improved shear strength

Analytics chart showing RPc / micro-roughness effects



Higher RPc and lower Roughness (Ra) tended to produce highest shear strength

Analytics chart showing RPc / micro-roughness effects



At lower cure temperature (95°C), Higher RPc maintains high shear strength

Conclusions

- Micro-roughness measurements have been shown to provide good correlation to resulting bond integrity, and should be used for control of production machined heatsinks
  - *Peaks per cm (RPc) above 500 (150x, 0.08mm cutoff filter) provide optimum bonding performance*
  - *Ra, when measured at 50x or higher (with 0.08mm cutoff filter) should be above 0.1μ to ensure adequate bond integrity*
- Conventional Ra roughness measurements will not ensure bond performance
- Micro-roughness parameters (both minimum cutoff / high magnification Ra and RPc) should be used to supplement conventional roughness range specifications for control of surfaces with critical bond integrity requirements
- With proper control of surface roughness conditions, low temperature cure of silicone TIM will provide excellent mechanical integrity