EFFECTS OF SURFACE ROUGHNESS ON EPOXY ADHESION STRENGTH BETWEEN ALUMINUM AND CARBON FIBER

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ABSTRACT

This experiment sought to determine the relationship between aluminum surface roughness, and the strength of its epoxy bond to carbon fiber. Uncovering how surface roughness factors into bond strength is essential for the design and manufacture of composite-aluminum hybrid components, used in high-load engineering applications. The experiment was conducted by first machining aluminum inserts of varying surface roughness, measured using the Mitutoyo SJ-201 Surface Roughness Tester. DP420 Epoxy was used to bond the inserts into carbon fiber tubes, which were then subject to a tensile test on an Instron. In 9 trials, with samples ranging from -0.49 to 3.47 µm in surface roughness, a relationship was found between surface roughness and peak force before failure. The relationship was parabolic, with the optimum surface roughness at 2.25 µm. It was also determined that varying surface roughness had no significant effect on the Young's Modulus, or stiffness, of the epoxy.

Keywords: Surface Roughness, Epoxy, Bond Strength, Carbon Fiber, Aluminum

INTRODUCTION

In many growing engineering industries, there is a constant need for designs and materials with high strength-to-weight ratios. Whether in the design of Formula-style race cars, industrial robots, or spacecraft, the use of carbon fiber composite material is essential for saving weight without sacrificing robustness. However, integrating carbon fiber into elements of mechanical designs does not come without challenges. Manufacturing is dangerous and often imprecise, and carbon fiber parts are weak under compression and buckling. As a result, carbon fiber is frequently bonded with precision-machined metal components to meet tolerances and strength requirements while mass is still optimized. Furthermore, chemical adhesion presents a promising alternative to welding, which often introduces many more manufacturing complexities and material limitations [1].

While the properties of carbon fiber have been heavily researched and analyzed, the efficacy of bonds between carbon fiber and non-composite materials is not as well understood. Furthermore, existing studies on optimizing inter-facial adhesion often arrive at conflicting conclusions due to varied control variables and procedures [2]. This experiment seeks to eliminate one independent variable in the bonding process by determining the effects of surface roughness on epoxy adhesive strength.

To investigate the effect of surface roughness on adhesive strength, nine samples of aluminum bonded to carbon fiber were manufactured and had their surface roughness measured with a Mitutoyo SJ-201 Surface Roughness Tester. Three samples were left with a machine finish, three samples were sandblasted for five seconds, and 3 samples were sandblasted for twenty seconds. Each sample subsequently underwent tensile loading in an Instron 68TM-50 Universal Testing System, where the force-displacement curve was recorded. A diagram of the carbon-fiber aluminum stack-up is given in Figure 1 on the following page. Using this data, a surface roughness vs. peak force and surface roughness vs. Young's Modulus graph were created. The Young's Modulus E of the carbon fiber was compared to the slope of the elastic region of the curve to explore any unexpected behavior caused by the epoxy bond.

PRIOR RESEARCH

There are numerous existing studies that test bonds between composite and non-composite materials, though both methodology and end results widely differ among them. Budhe used epoxy resin to bond 6061 aluminum, varying the surface roughness through mechanical abrasion, specifically with emery paper and sandpaper [1]. No linear relationship between surface roughness and bond strength was observed, but a roughness value of 1.68 ± 0.14 µm was found to result in the strongest bond. Van Dam et al. determined through single lab joint shear tests that the strongest bond was formed when grit-blasted to a surface roughness of 1.02 ± 0.22 µm [2]. Van Dam's study, however, never tested any samples rougher than 1.02 µm. One factor in which these previous studies differ from this one is that the samples are planar instead of cylindrical aluminum inserts and carbon fiber tubes. The only previous experiment that used cylindrical parts

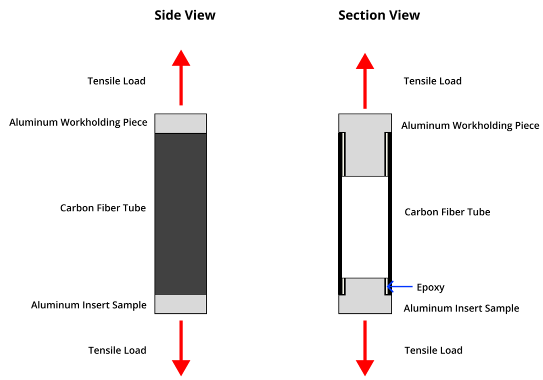

FIGURE 1: Diagram of the experimental setup. Both images show the same set-up, one with a side view and one with a section view. In the experiment, the tensile load will be introduced through an Instron 68TM-50 Universal Testing System.

was by Sekercioglu, who determined that surfaces with a surface roughness of less than 1 µm or more than 2.5 µm had very low maximum shear stresses. It was also found that for the same surface roughness, static and dynamic loading produced very similar results [3].

THEORY

These previous studies largely reference empirical data and manufacturer specifications instead of physical models and formulas. Van Dam et al. and Leena et al. reference other studies in their work, never citing any theory [2–4]. Budhe et al. concluded that from previous studies, there was no general trend correlating surface roughness to adhesion, due to differences in set up, pretreatment and loading [1]. Only Kwon et al. referenced a possible theory, by relating adhesion strength to aluminum's surface energy. The surface energy is the work per unit area that a surface performs on the material it interfaces with. The more surface energy a material has, the more "wettable" and susceptible to adhesion it is. The greater the surface roughness, the more surface energy it will have, due to an increased surface area[5]. Kwon et al. further verify this theory, finding a positive linear relationship between surface roughness and W_a, the adhesive work done between the adhesive and adherent [6]. Though epoxy bonds are widely used in both commercial and industrial applications, the theory of how surface roughness affects adhesive strength is complex and not fully developed. However, the relationship found in Kwon's study shows promise in taming the unpredictability of epoxy bonds. Sekercioglu also attempts to relate surface energy to maximum adhesive strength but hypothesizes that too rough of a surface leads to lower wettability, leading to a decaying epoxy strength past a surface roughness of 2.5 µm.

EXPERIMENTAL DESIGN

Lathed aluminum inserts of varying surface roughness were inserted in identical carbon fiber tubes and bonded with DP 420 epoxy. The average surface roughness R_a of each insert was recorded using a Mitutoyo SJ-201 surface tester. R_a is computed by taking the average of the surface profile's deviations from the measured mean profile height. R_a vs sandblasting time is shown in Figure 2. Once the epoxy was cured, each assembly underwent a tensile test with an Instron 68TM-50 Universal Testing System, which introduced a tensile load on the sample insert. The force-position curve and the peak force before the epoxy failed were recorded.

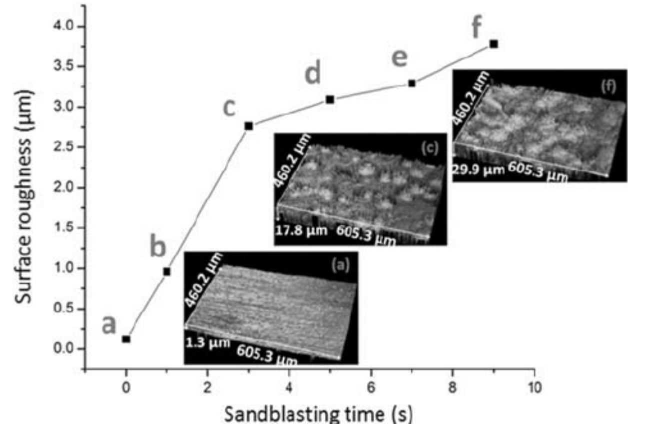

FIGURE 2: Figure displaying R_a vs sandblasting time for copper samples [7]. The images show a microscopic view of the surface profiles after different sandblasting durations.

Sample Preparation

Each sample was prepared following the process seen in Figure 3. Many of these steps were completed in parallel between samples, most notably the chemical treatment and sandblasting. Machining the aluminum inserts was by far the most time-consuming. Furthermore, as each process was manually timed, the chemical treatment, sandpaper abrasion, and sandblasting processes were not completely identical between trials, thus contributing to uncertainty.

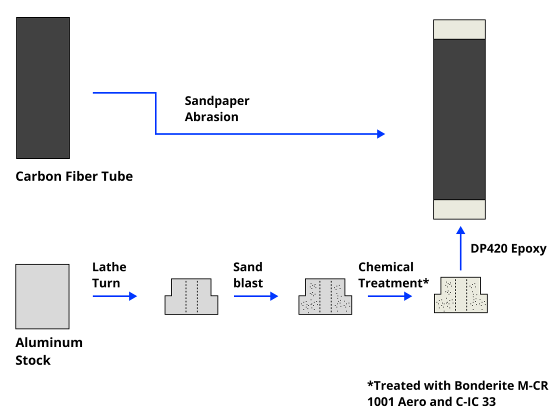

FIGURE 3: Schematic of the sample preparation process. Each arrow represents a process the sample underwent. The carbon fiber tube and aluminum inserts were manufactured and treated in parallel until they were combined using DP420 Epoxy.

In this experiment, each carbon fiber tube was approximately

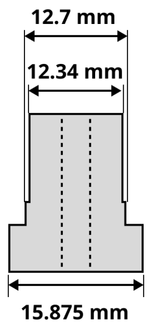

FIGURE 4: Dimensions of aluminum insert, from a side profile. The largest diameter of 15.875 mm is equal to the outer diameter of the carbon fiber tubes. The small lip of diameter 12.7 mm is an aligning feature the same size as the tube inner diameter, to ensure insert concentricity. The smallest diameter is the inner diameter of the carbon fiber tube minus the specified bond gap of .178 mm.

50 mm in length, with an inner diameter of 12.7 mm and an outer diameter of 15.875 mm. The aluminum inserts were lathed to the dimensions seen in Figure 4.

After the inserts were machined, 3 of them were left with a machine finish, 3 of them were sandblasted evenly for 5 seconds, and 3 of them were sandblasted evenly for 20 seconds, each timed with a timer. These 9 samples were split into 3 groups of 3 trials. Trials 1, 4, and 7 were left at a machine finish, trials 2, 5, and 8 were sandblasted for 5 seconds, and trials 3, 6, and 9 were blasted for 20 seconds.

The inserts then went through a series of chemical baths for epoxy pre-treatment. Each insert was submerged in a 1:3 solution of Bonderite C IC-33 Aero and Water for five minutes, dunked in water, then submerged in a 1:2 solution of Bonderite M-CR 1001 for five more minutes. Bonderite C IC-33 Aero was used to chemically clean the inserts, and Bonderite M-CR acted as a corrosion-proofing agent.

3M DP420 Epoxy was used to adhere to the insert and the carbon fiber. According to 3M, the tested overlap shear strength of DP420 with acid-etched and degreased aluminum is 17.23 MPa. There are no specifications for DP420's strength in carbon fiber adhesion. Once the epoxied inserts were fit in each tube, they were left to cure at room temperature for 24 hours.

This curing procedure was repeated twice: once for trials 1 through 3 and once for trials 4 through 9.

Surface Roughness Measurement

Before the epoxy was applied, the surface roughness of each insert was measured with a Mitutoyo SJ-201 Surface Roughness Tester axially across the sandblasted surface. The measurements spanned across three distinct regions along the insert's circumference. These values were then averaged, taking into account the uncertainty of each individual data point as well as the uncertainty from averaging.

Position-Force Measurement

Each cured sample was subjected to tensile loading using an Instron 68TM-50 Universal Testing System. One 1/4-28 threaded stud was threaded into each side of a sample, and placed into the Instron's 50kN manual wedge grips. The Instron automatically collected vertical displacement vs. force data for each trial.

RESULTS AND DISCUSSION

Surface Roughness and Force-Displacement Curve

The nine samples had their surface roughness measured in three different locations. The three samples that were not sandblasted were categorized as "machined finish", while the sandblasted samples were labeled "blasted 5s" and "blasted 20s" respectively. These results are seen in Figure 5

Due to the random nature of sandblasting, some variation was observed in each category. However, the difference in roughness between categories was still significant. The average surface roughness for the three machined finish samples was 0.58 ± 0.10 µm. For the blasted 5s samples, the average was 1.98 ± 0.96 µm. The variation in these samples was especially high, because it was difficult to ensure an even sandblast coating in exactly 5 seconds, so the amount each sample's surface was treated varied a significant amount. The average surface roughness for the blasted 20s samples was 1.98 ± 0.96 µm. Due to the high uncertainty in each average, the surface roughness of each sample was individually plotted in future analyses and graphs.

The force-displacement data was collected and plotted for all nine trials. It was found that all trials followed began with a nonlinear, seemingly random force-displacement relationship, and were followed by a roughly linear region in which the force steadily increased until failure. The force-displacement curve for trial 1, as well as trials 4-6, are shown in Figure 6.

As seen in Figure 6, besides the first 0.25 mm of displacement, the rest of the curve is quite linear. Though this is not reflected in every trial, each one had at least a 0.5 mm section of linearity. This section was used to calculate the Young's Modulus E of the epoxy in each sample. The force where the sample failed was the peak force, which spanned from 4.16 to 9.1 kN, and a near vertical drop in force followed in every trial. In many trials, there were various dips in the peak force along the curve, most notably in the trials with the highest peak force values. This may be due to small sections of the epoxy yielding before total failure. It may also be likely that the work-holding solution between the sample and the Instron was not perfect, and the wedge grips slipped occasionally on the threads of the 1/4-28 studs. From the linear region, the experimental Young's Modulus was derived, as seen in Figure 7.

To calculate the Young's Modulus, both the inner radius and length of the carbon fiber tube were measured. Each carbon fiber tube was approximately 50.8 mm in length and had a radius of 6.35 mm. The length of the tube was set as the initial length L_0, and the true strain of each sample was calculated using the formula:

$$e = \ln \frac{L_0 + \Delta L}{L_0}$$

The stress was calculated by dividing the force F by the surface

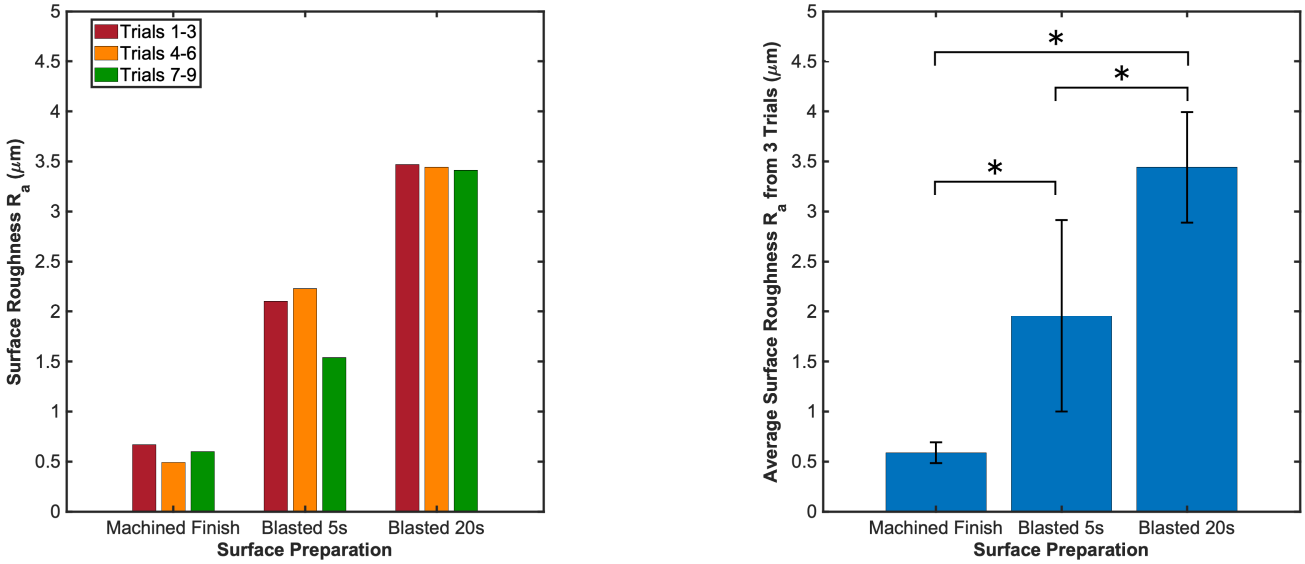

FIGURE 5: Average surface roughness vs. surface preparation method measured using the Mitutoyo SJ-201 Surface Roughness Tester. The graph on the left represents the surface roughness measured from each individual trial, while the right graph represents the average surface roughness for each preparation method with uncertainty. The error bar shows the propagated uncertainty from each trial. A t-test was performed between the sandblasting methods, which showed that there is a statistically significant difference in surface roughness between each method. The average surface roughness was measured to be 0.58 ± 0.10 µm for the machine-finished samples, 1.98 ± 0.96 µm for the 5s sandblasted samples, and 3.44 ± 0.55 µm for the 5s sandblasted samples. These roughness values were the independent variable in all future data analyses.

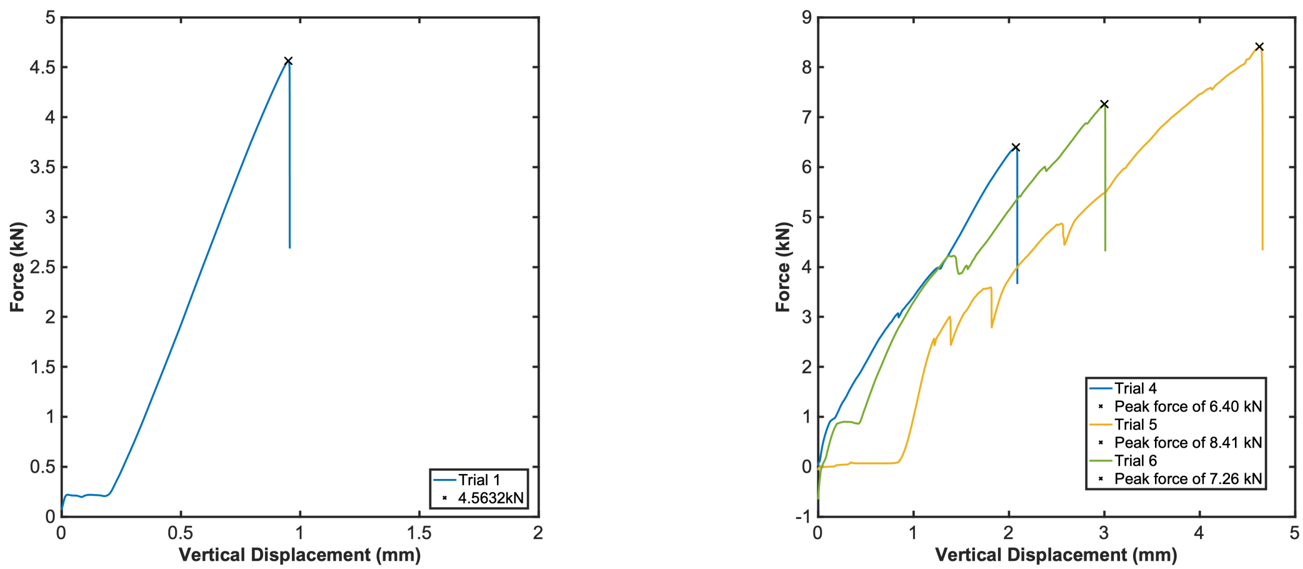

FIGURE 6: Representative force vs. displacement graph on the top, from the first trial. Stacked force vs. displacement curves for trials 4 to 6 on the bottom. The peak force is marked with an "X", and is 4.56 kN for trial 1. This is the force in which the epoxy yielded, marked by the sudden drop in force after that mark. The peak force from this and the other 8 trials were compiled to plot the peak force vs. surface roughness graph. The linear region of this graph was cropped and converted to a stress-strain curve to calculate Young's Modulus E for each trial. Most of the graphs followed a similar pattern but had occasional nonlinear regions due to unknown epoxy material behavior.

area of the bonded region:

$$\sigma = \frac{F}{4\pi r L_{insert}}$$

Using these formulas, the stress-strain curve for the linear segments of each trial was generated. The stress-strain curves were fit with a linear one-parameter fit, with the highest uncertainty among the trials being from trial 7, at $\pm$ 3 MPa.

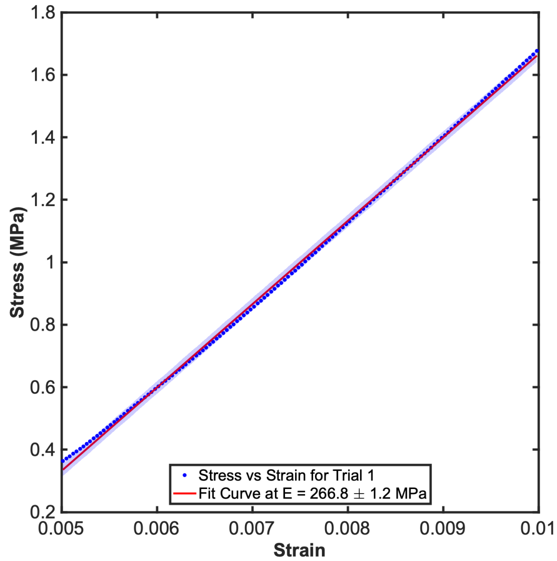

FIGURE 7: Representative stress vs. strain graph, calculated using the force vs. position data from the first trial. The red line is a linear fit with the equation ax, where a = 266.8 $\pm$ 1.2. Since the stress is zero when the there is no strain, there is no constant parameter. The strain was found using the true strain equation and the initial sample length. The stress was found by dividing the force by the epoxy bonded surface area. The red line represents the fit Young's Modulus value of 266.8 $\pm$ 1.2 MPa. The 95% confidence interval is shaded in blue.

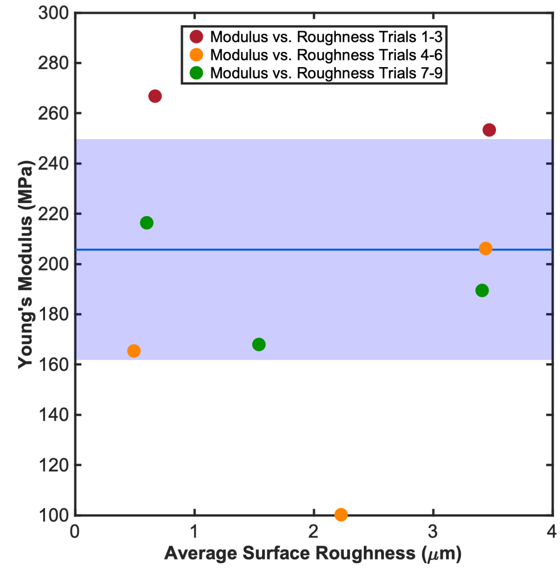

FIGURE 8: Young's Modulus vs. average surface roughness, fitted with an average line. Trials 1-3 are in red, Trials 4-6 in yellow and 7-9 in green. The 95% confidence interval is shaded blue. Young's Modulus E was first fitted with a quadratic fit, but no parameters were deemed significant. As a result, an average Young's Modulus of 205 $\pm$ 43 MPa was plotted instead. The average surface roughness has no discernible effect on the Young's Modulus of the epoxy. This makes sense, as the surface roughness wouldn't affect the elastic properties of the cured epoxy. The variation in Young's Modulus seen here would be more likely due to differences in curing conditions or the epoxy mixing ratio, as DP420 is a two-part epoxy.

Young's Modulus vs. Surface Roughness

In an attempt to discover how the epoxy's stiffness varies in relation to surface roughness, each trial's calculated Young's modulus was plotted in relation to its measured roughness. However, as seen in Figure 8, no discernable relationship was found.

When fit to a quadratic curve, none of the parameters besides the constant term were significant, which suggests that an average is a much better approximation of the Young's Modulus, and it does not depend on the surface roughness. The average Young's Modulus was 205 $\pm$ 43 MPa.

The differences in Young's Modulus are not due to surface roughness but are most likely due to the individual curing process for each sample, which is beyond the scope of this experiment. Also, the 3M DP420 epoxy is a two-part epoxy and relies on a mixing tube to ensure the proper mixing ratio. Slight differences in the ratio in practice may have also contributed to the variance in this data.

Peak Force vs. Surface Roughness

The main objective of this experiment was to determine a relationship between aluminum's surface roughness and its adhesive strength with carbon fiber. The variable most representative of maximum adhesive strength is the peak force before yielding, a data point that was collected from each trial. Figure 9 shows each point plotted on a peak force vs. average surface roughness graph, with a quadratic curve fit to the data.

As seen above, it is likely that peak force and surface roughness have a roughly parabolic relationship. The fit suggests that the adhesive strength is the greatest at a surface roughness of 2.25 µm. This theoretical maximum corresponds with Sekercioglu's experimental results, as they observed a peak strength from 1.65 to 2.0 µm [3]. Van Dam's study also corroborates this data, through an observation of a sharp increase in adhesive strength from a mirror finish to a grit-blasted aluminum sample [2]. This data suggests further corresponds with the surface energy theory posed by Kwon et al [6]. Surface energy, a measure of how easily liquid adheres to a surface, is in the form $\frac{energy}{area}$. A higher surface energy is correlated to a surface being more wettable. Roughening a surface increases the total surface area of the surface without increasing its other dimensions. This means that as surface roughness increases, as long as the material's surface energy stays constant, the total surface energy across each sample increases too. The higher the surface energy, the easier the epoxy adheres with the aluminum and the stronger the epoxy's bond is. The subsequent decrease in adhesive strength is not well understood, but it may be due to a decrease in wettability at extreme surface roughness. On a microscopic level, the profile deviations of the surface may be too large for the epoxy to spread and cover every crevice of the surface, especially if the cohesive forces of the epoxy itself are very large. This would cause microscopic gaps between the epoxy and the surface itself.

Determining a range where the aluminum-carbon fiber bond is strongest is instrumental to the design and analysis of many

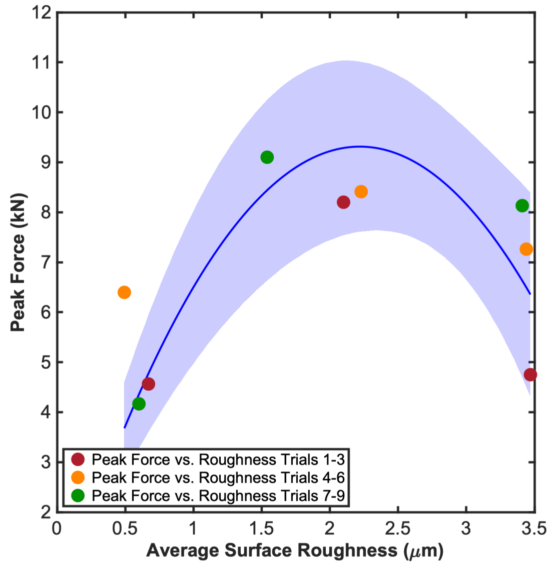

FIGURE 9: Peak force vs. average surface roughness of each trial, fitted with a quadratic curve. Trials 1-3 are in red, Trials 4-6 in yellow and 7-9 in green. The 95% confidence interval is shaded blue. The curve is in the form $F = Ar^2 + br$, where $A = -1.89 \pm 0.70$, and $B = 8.4 \pm 2.2$. The constant parameter was removed because it was insignificant; the uncertainty is larger than the value. In the actual physical setup, the peak force would always be positive, even at a surface roughness of 0 µm. The quadratic fit signals a theoretical peak force at a surface roughness of 2.25 µm. However, the large uncertainty in the curve fit suggests that there are many other factors, other than surface roughness, that affect the peak force significantly.

structural systems, especially in cutting-edge engineering applications. On the basis of this data, aluminum-composite interfaces undergoing tensile loads should be prepared to a surface roughness of 1.5 to 2.5 µm to withstand the highest load. Having this knowledge will enable engineers to shave off additional mass with confidence and create a standard in aluminum surface preparation.

Though these results are supported by both prior research and theory, with such high uncertainty values, the conclusions are not absolute. uncontrolled variables such as the roughness of the carbon fiber tubes themselves, specific curing humidity and temperature, and uneven surface roughness along samples increase the variability in the data significantly. Further, due to initial inexperience, the machining, surface preparation, and epoxy bonding improved as subsequent samples were manufactured. This could explain the higher average peak force in trials 4-9, compared to trials 1-3. In future studies, varying other parameters, such as curing temperature, bondable surface area, or epoxy type, may offer a clearer insight into the optimizations necessary to maximize epoxy adhesive strength.

CONCLUSIONS

Through this experiment, a parabolic relationship was determined between the tensile strength of aluminum and its surface roughness, when epoxy bonded to carbon fiber. Though there is significant uncertainty, the theoretical peak force was found to be at a surface roughness of 2.25 µm. This agrees with the values found in previous research of varying methods, especially with studies conducted by Sekercioglu [3] and Kwon [6]. There was no correlation found between surface roughness and the stiffness of the bond, which had an average Young's Modulus of 205 $\pm$ 43 MPa. In engineering applications ranging from designing formula-style race cars to manufacturing rockets, understanding optimum surface preparation is crucial for robust yet lightweight aluminum-composite components. Future experiments should study the effects of different parameters, such as curing temperature, epoxy type, and surface area, for a more holistic understanding of hybrid composite design.

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