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Investigating the Influence of Surface Roughness on Metal Bonding Using Response Surface Methodology †

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Abstract: The present study deals with the parameters for Stainless Steel 304 and Aluminum 5083 optimized with an emphasis on surface roughness, cure time, and their impact on the tensile strength of single-lap shear joints. Utilizing a central composite design, the effects of these factors were examined. Acetone was used to polish the surfaces, and silicon carbide sheets (P30, P36, and P60) were used to abrade them. Utilizing Henkel Loctite HY4090 glue, testing was conducted in accordance with ASTM D1002 guidelines. The variables were optimized with Design-Expert 11. Maximum tensile strengths were obtained with P30 abrasion and a 48-h cure time for SS304 (Ra = 3.2 μm) and Al5083 (Ra = 5 μm), respectively.

Keywords: tensile strength; adhesive bonding; surface roughness

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1. Introduction

This article illustrates how surface roughness and cure time, optimized with RSM, affects the tensile strength of joints between both identical and different materials bonded with adhesive. For the tensile test, both Aluminum 5083 and Stainless Steel 304 samples were prepared according to ASTM D1002 [1]. The test settings were established using the Design-Expert program RSM (Response Surface Methodology). Two criteria—surface roughness and cure time—were utilized to investigate their impact on the strength of joints bonded with adhesive. Silicon carbide sheets of varying grades were utilized to improve the surface roughness of both adherend materials. The surface roughness of both materials was determined using a device called a Profilometer. The bond strength of the adhesively bonded specimen was determined using a tensile test on a universal testing machine (UTM). For joining different or comparable structural components, adhesive bonding is regarded as a crucial technology with a range of uses in the aerospace, automotive, biomedical, and microelectronics industries, amongst others [2–5]. To attain the necessary adhesion bond strength, researchers attempt to obtain the best possible adhesion between the adhesive and the adherends [6]. Testing setting, adhesive thickness of bond, adherend surface shape, and surface preparation have all been found to have a significant impact on adhesion phenomena [7]. Adhesively bonded connections are now often used in a wide variety of systems or constructions. The improvement of high-quality adhesive-bonded connections can lead to an increase in load distribution, impact behavior, and material service life. Additionally, it can reduce manufacturing complexity, machining costs, and vibrations [8]. Adhesively bonded joint failures are characterized as a proportion of cohesive or adhesive failure and are frequently prone to many modes of failure. Based on the percentage of surface area in contact that is susceptible to cohesive or adhesive failure, this percentage is simply estimated [9,10]. Surface preparation is critical for getting the highest tensile

strength between the chosen adherend and adhesive. There is no point at which maximal bond strength can be obtained; rather, there is a limit. Surface roughness first increases until it reaches a maximum, after which it begins to diminish [11]. Optimization entails improving the system's performance to get the greatest advantage achievable. It is an analytical approach for predicting the conditions in which maximum performance may be achieved while remaining within restrictions [12]. Traditionally, experiments are conducted so that one component is changeable while the others stay constant. This method of optimization is referred to as one-variable-at-a-time. The primary shortcoming of this optimization approach is that it does not explain the link between the variable and constant elements. The second drawback is that it increases the number of tests that need to be done to acquire results, resulting in a waste of time and money [13,14]. RSM is mostly used in the industrial world to ensure the functionality and quality of a given product or process. These outcomes are referred to as replies. In the real world, these answers are influenced by several factors. Before implementing RSM, it is important to define the parameters that will influence the system's outcomes and reactions. These characteristics may include feed rate, velocity, and material weight [15].

The objective of the research is to enhance surface roughness to get the highest binding strength between the selected adhesive and the adherend. It is necessary to examine the shear bond strength of adhesively bonded metal substrates with different surface roughness and cure times.

2. Material and Methods

In this study, the tensile strength of two alloys, Al5083 and SS304, was calculated using Henkel Loctite HY4090 adhesive. Al5083 and SS304 were bought from Metal House, Lahore and their properties are shown in Table 1. To remove foreign particles from the substrate surface, laboratory-grade acetone was used. LOCTITE 4090 is a two-part/component epoxy with a mixing ratio of 1:1 and is applied with a mixing gun to provide the best mixing ratio. The properties of LOCTITE 4090 are shown in Table 2. The technical data sheet for LOCTITE 4090 demonstrates that the rate of cure is temperature- and time-dependent. To attain full strength, all samples were given different cure periods of 24, 36, and 48 h for adhesion at room temperature. Because of its thixotropic properties, it works well in applications where uneven and poorly fitting surfaces need good gap-filling capabilities. Samples of both adherend materials were manufactured according to the ASTM D1002 criteria for single-lap joint testing. The adherends were fabricated to specifications, measuring 1.62 ± 0.125 mm thick and 25 mm wide. Each sample had an overlap length of 12.7 ± 0.25 mm to ensure consistency between experiments. The total length of adherend material utilized in each sample was 100 mm. During testing on a universal testing machine (UTM), the adherend was fixed with a jig length of 25.4 mm to ensure uniformity and precision throughout the assessment procedure. To ensure a reliable comparative study of the adherend material performance under standardized settings and to meet ASTM D1002 criteria, these preparations were essential. Using a face-centered design and a central composite technique, Design-Expert software was utilized to decide on the design and quantity of testing. The relationship between surface roughness and tensile strength was chosen to be systematically investigated using the central composite technique and face-centered design. For examining the effects of surface roughness at different levels and figuring out the interactions, these experimental designs offer a strong basis. Certain types of round silicon carbide paper (P30, P36, and P60) were used in order to increase surface roughness, following the guidelines provided by FEPAP. Additionally, laboratory-quality acetone was used to reduce ambient pollutants and enhance surface roughness. The adherend material surface roughness was measured using a profilogram, and adherent material samples were produced in compliance with ASTM D1002 (single-lap joint test) as shown in Figure 1. ASTM D1002 standards mandate the use of 78 samples with varying surface roughness and a stroke feed rate of 1.3 mm/min for tensile testing in a universal testing machine.

Table 1. Properties of alloys.

Alloy	Tensile Strength (ksi)	Yield Strength (ksi)	Elongation (Inches)	Tensile Strength (Mpa)	Yield Strength (Mpa)	Elongation (% in 50 mm) min
Aluminum 5083	39.1602	16.6793	0.472441	270	115	12
Stainless steel 304	89.9234	44.6716	1.5748	620	308	43

Table 2. Properties of Henkel Loctite Hy 4090.

Technology	Cyanoacrylate/Epoxy hybrid
Type of chemical (Part A)	Cyanoacrylate
Type of chemical (Part B)	Epoxy
Appearance (Comp. A)	Transparent colorless to straw-colored liquid
Appearance (Comp. B)	Off-white to light-yellow gel
Appearance (Mixture)	Off-white to light-yellow gel
Mix ratio, by volume Part A:Part B	1:1
Cure	Room temperature cure after mixing
Viscosity	High
Application	Bonding



Figure 1. Prepared adherend material.

3. Results

A total of 78 samples with varied surface roughness were prepared for both adherend materials. The surface roughness Ra value and adherend material profilogram for SS304 and Al5083 are provided below in Table 3.

Table 3. Ra values of SS304 and Al5083 with mechanical abrasion.

Stainless Steel 304	Surface Roughness
P60 paper	1.3 ± 0.2 µm
P36 paper	2.25 ± 0.2 µm
P30 paper	3.2 ± 0.2 µm
Aluminum 5083	**Surface Roughness**
P60 paper	0.5 ± 0.2 µm
P36 paper	2.75 ± 0.2 µm
P30 paper	5 ± 0.2 µm

3.1. Surface Roughness Comparison after Mechanical Abrasion

The adherend material samples that were examined after being treated with various silicon carbide sheets are compared side-by-side in the table given below.

3.2. Lap Shear Strength of Adherend Specimen

The adherend samples were created in compliance with ASTM standard D1002, and the UTM Trapezium X was used for the testing. Three samples with varying surface roughness were examined at a loading rate of 1 mm/min. The stroke feed rate of 1.3 mm/min relates to how quickly the crosshead of the universal testing machine (UTM) travels during the tensile test. This number is set in the ASTM D1002 standard to provide consistent testing conditions and accurate findings. A loading rate of 1 mm/min is the rate at which the load is delivered to the samples during tensile testing. Comparison of surface roughness and tensile strength for adherend material is given below in Figure 2.

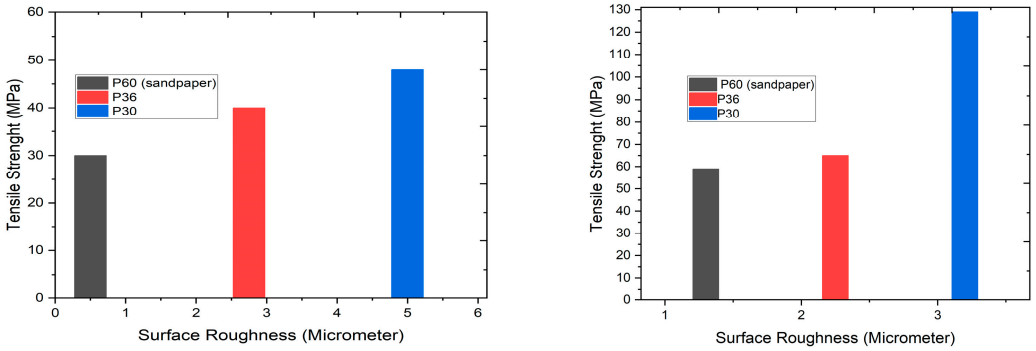


Figure 2. Surface roughness vs. tensile strength for adhesive joint: (**a**) Al5083, (**b**) SS304.

3.3. Effect of Cure Time on Tensile Strength

The adherend samples were bonded in accordance with the ASTM D1002 standard, and three cure times—24, 36, and 48 h—were chosen to ensure that the bond was completed, as cure time gives the adhesive more opportunity to form a stronger bond with the adherend material. The tensile strength of the adhesively connected material improves as the cure time increases as shown in Figure 3. The difference in cure time given to the adhesive-bonded joints to settle on the adherend surface is represented by the following graphs. The tensile strength of SS304 is 59 MPa after a 24 h cure time, and it grows to 129.3 MPa after a 48 h cure time. Similarly, the tensile strength of Al5083 starts at 31 MPa and climbs to 44.04 MPa with increasing time. This change in the first phase shows that the material's intrinsic qualities take precedence, and the increase in surface roughness is inadequate for meaningfully affecting tensile strength.

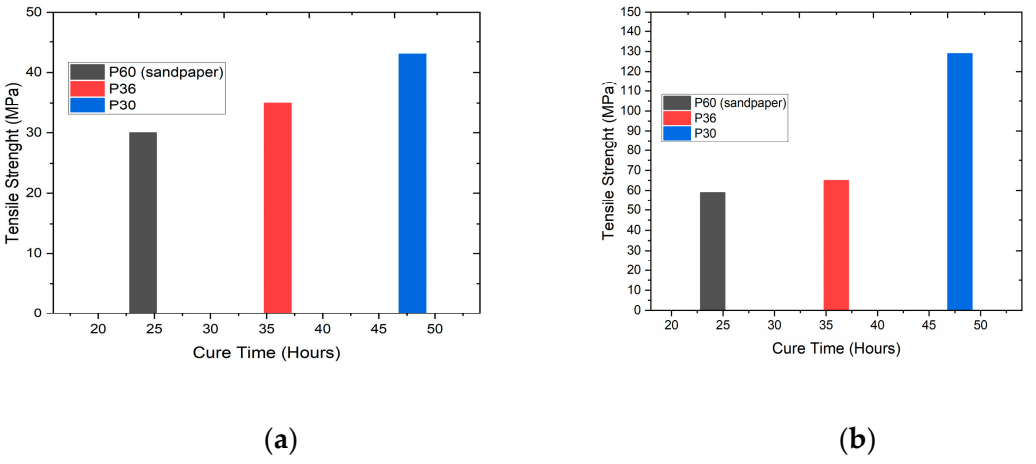
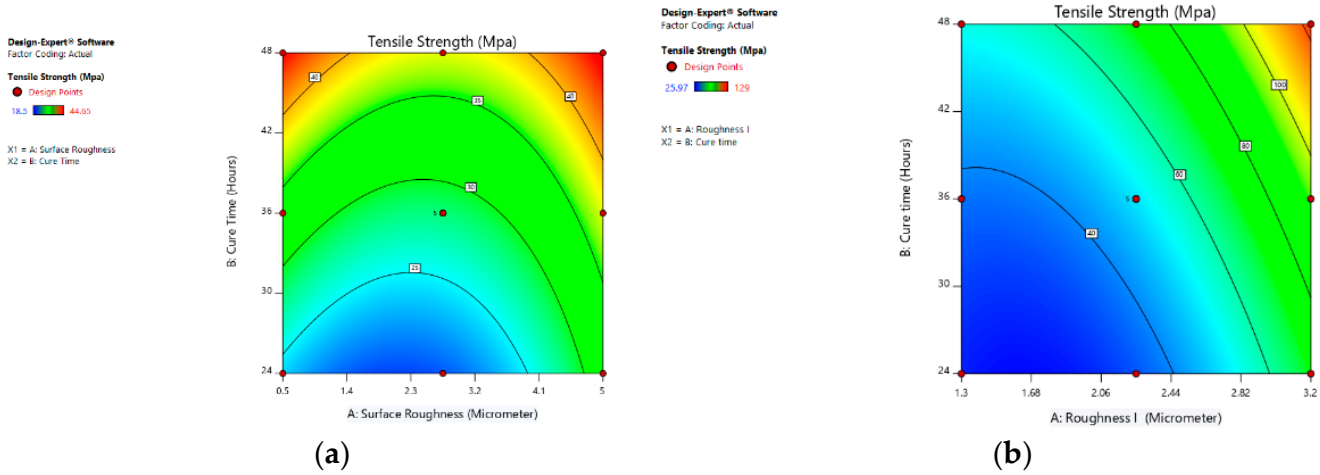


Figure 3. Effect of cure time on tensile strength: (**a**) Al5083; (**b**) SS304.

Increasing the surface roughness of adherend material improves mechanical interlocking with adhesives, potentially boosting bond strength. Similarly, longer curing durations enable more thorough cross-linking of the adhesive, resulting in stronger connections due to better molecular adhesion.

3.4. Effects of Independent Variable on Tensile Strength

The quadratic influence of the variables on tensile strength, which rises as surface roughness and cure time increase, are illustrated below in Figure 4.



(**a**) (**b**)

Figure 4. Strength contour plot for (**a**) Al5083, (**b**) SS304.

3.5. Point Prediction

RSM offers the ideal settings based on these experiments to maximize bond strength. For A5083, the optimized variables recommend a surface roughness of 5 µm and a cure period of 48 h to achieve a maximum tensile strength of 45.29 Mpa. The design is suitable for usage, as shown by the desirability of 1. Similarly, the optimal parameters for adherend SS304 state that a surface roughness of 3.2 µm and a cure period of 48 h are required for a maximum tensile strength of 123.15 MPa. Given that the desirability is higher than 0.971, the design can be used.

3.6. Verification of the Experiments

These parameters were the subject of experiments, and the findings indicated that there was an acceptable error between the predicted and experimental values. These findings thus supported the suitability of RSM equations for the response (Table 4).

Table 4. Predicted and experimental values for Al5083 and SS304.

	Response	Predicted Value	Experimental Value	Percentage Error
Al5083	Tensile strength	45.56	44.23	2.22%
SS304	Tensile strength	123.1	120.6	2.55%

4. Conclusions

There are two results from this entire study project. As the roughness of the surface grows, (1) the tensile strength grows, and (2) the cure time increases. The RSM model was used to achieve accurate findings, with a low percentage error between predicted and obtained values. The results show that the models developed using RSM are suitable and may be utilized in future research, demonstrating that RSM is an effective optimizing technique. To achieve maximum bond strength of 45.29 Mpa, Al5083 specimens should be mechanically treated with P30 abrasion paper, have a surface roughness of 5 µm, and

the cure period should be 48 h. Surface roughness of 0.5 µm and a cure period of 24 h result in a minimum tensile strength of 25.8 MPa. To achieve maximum bond strength of 129 MPa, SS304 should be mechanically pretreated with abrasion paper P30, have a surface roughness of 3.2 µm, and curing time should be 48 h. The minimum bond strength is achieved when the surface roughness is 1.3 µm and the cure period is 24 h.

Author Contributions: M.S. conceived the study and designed the experiment. M.A.M. conducted the experiment and collected the data under the supervision of M.A. The data were analyzed by M.A.M. and M.A. The manuscript was written by M.A.M. Project supervision was carried out by M.S., M.A. and T.I.K. All authors have read and agreed to the published version of the manuscript.

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