Budhe *et al. Appl Adhes Sci (2015) 3:20*
DOI 10.1186/s40563-015-0050-4

Applied Adhesion Science
a SpringerOpen Journal

RESEARCH
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Effect of surface roughness using different adherend materials on the adhesive bond strength

S. Budhe[1*], A. Ghumatkar[2], N. Birajdar[3] and M. D. Banea[1]

*Correspondence: sandipiit@gmail.com
[1] CEFET/RJ, Federal Center of Technological Education in Rio de Janeiro, Av-Maracanã, 229, Riode Janeiro, RJ 20271-110, Brazil
Full list of author information is available at the end of the article

Abstract

In this paper, an experimental study on the effect of surface roughness of different adherend material on adhesive bond strength was carried out. The adherend material used was aluminium AA6061 and wood in the form of sheet, and the adhesive was an epoxy resin. Different surface roughness obtained by mechanical abrasion using an emery paper and sand paper for aluminium and wood adherend samples respectively. Single strap joints were tested at room temperature. Results showed that there is clear dependency observed in between the adhesive bond strength and surface roughness of both wood and aluminium adherend joints. Optimum surface roughness values were obtained in the range of $R_a = 1.68 \pm 0.14$ µm and $R_a = 1.64 \pm 0.2$ µm for the aluminium and wood adherend joints respectively. Surface roughness along with the adhered material parameters should be considered during design stage of adhesively bonded joints.

Keywords: Adhesive bond strength, Surface roughness, Adherend material, Single strap joint

Background

Mechanical performance of adhesive bonded joints depends on a number of parameters such as: material properties and joint geometry (adhesive thickness, adherend thickness), surface roughness etc. [1]. Therefore these parameters have a great importance in industrial application for achieving maximum strength. During the design of adhesively bonded joints, one has to take into account these factors associated with the bond strength. A number of researchers [2–6] have examined the effect of different parameters on the strength and durability of adhesive joints. The nature of the adherends has highly influence on the strength of the adhesive bond.

Surface roughness is one of the important factors which influence the mechanical properties of the joints. The relationship between the surface roughness and adhesion is very complex. Most of the researchers [7–9] noticed the importance of surface and its positive influence on the bond strength. There are different surface treatments methods available such as grinding, grit blasting, mechanical etching, plasma, chemical etching etc. Critchow and Brewis [2] studied the influence of adherend surface roughness on the durability of adhesive bonding joints. Surface roughness was achieved by grit blasting method. They observed that roughness has a significant effect on durability of epoxy-Al joint. Dayss et al. [10] investigated the effect of surface roughness of polymer adherend on adhesive bond strength. Mechanical grinding and low-pressure plasma treatment was used for modifying surface properties. It was found that increased roughness led to improvement in bond strength, but there was a limit of around 1 MPa. Tezcan et al. [11] studied the effect of surface roughness on the strength of adhesive bond under static and dynamic conditions. It was observed that low roughness values gave the lowest static strength and load cycle values. For roughness values of $R_a = 1.5$ to 2.5 μm, the static strength showed a decreasing trend while from $R_a = 0.5$ to 2 μm, the highest number of load cycles were obtained. Baburaj et al. [12] noticed an enhancement of adhesive joint strength by laser surface modification. Uehara [13] concluded that an optimum surface roughness value exist for the maximum tensile strength. However, no clear relationship was observed between the peel strength and the surface roughness. Zhang et al. [14] investigated the effect of surface pre-treatment on adhesive properties of aluminium alloys. They found that maximum lap shear strength and durability of adhesive bonding joints can be improved by surface treatment and roughness modification. On the other hand, the surface roughness of wood is influenced to a much higher degree by environmental factors such as temperature, humidity etc. than a metallic structural material like aluminum. For wood adherend joints, the lower surface roughness value (smoother surface) gives the higher bond strength joint [15, 16].

As summarized above, there is no general trend which relates the surface roughness with the strength of adhesive bonded joints. An optimum surface roughness range is differing with respect to the adhesive-adherend combinations in order to get high performance of bonded joints. Therefore, for different adhesive-adherend joints, there will be a different optimum range of roughness with regard to bond strength. It is of interest to study the change in behaviour of adhesively bonded joint with change in adherend material. The objective of the present study is to investigate the influence of surface roughness using aluminium and wood adherend material on the adhesive bond strength.

Experimental details

Methods

The materials used in this study were aluminium AA6061 adherend, keeping in mind that it is extensively used in structural applications because of its lightweight. Chemical composition and mechanical properties of Aluminium AA6061 is presented in Table 1 (data from supplier). Aluminium plates of size 100 × 25 × 5 mm were cut by shearing from the commercially purchased sheet. An epoxy resin, commercially known as Araldite® 2015 [Huntsman Advanced Materials (India) Pvt. Ltd.], was used. Subsequently, wood

Table 1 Chemical composition and mechanical properties of Aluminium AA6061

Chemical composition (%)							Mechanical properties		
Fe	Mg	Si	Cu	Zn	Cr	Al	Ultimate tensile strength (MPa)	Yield strength (MPa)	Elongation (%)
0.35	1.0	0.6	0.25	0.15	0.20	Balance	310	275	15

was used as the adherend material. Wood billet of size 100 × 25 × 10 mm were cut by planning operation from commercially purchased wood.

The surface roughness of the aluminium adherend was varied by mechanical abrasion using an emery paper. Different grades of emery paper identified by P120, P50 and P30 were used to produce different levels of surface roughness and as-purchased aluminium plate surface roughness was itself used as one grade. The residual particles remaining after mechanical abrasion were removed by cleaning the surface with a soft clean cloth. For wood adherends, the surface roughness was varied by mechanical abrasion using sand paper. Different grades of sand paper identified by P120, P80 and P50 were used to produce different level of surface roughness and wood billet after planning operation was itself used as a one grade.

Surface roughness of treated and untreated samples was measured using a profilometer (Pocket Surf Make Mahr, GMBH, Model EMD 1500). The measuring range of the profilometer was 0.03–6.35 µm, while the sensor traversing length for all cases was 10 mm. Two roughness parameters, namely average roughness (R_a) and maximum roughness (maximum height of profile, R_z) were used to evaluate surface roughness of the specimens. Measurements were performed in different areas, along two different mutually perpendicular directions, longitudinal and tangential.

The surface treatment of the aluminium adherend was done by wiping once with acetone and subsequently soaking those in 20 % by weight NaOH solution. Adhesive was applied on the adherend surface and spread over it with the spatula. The adhesive thickness was 0.35 ± 0.04 mm. The specimens were then bonded by applying constant pressure on specimens for 48 h. The curing time was set to 48 h at room temperature. For the wood adherend samples, the surfaces were wiped by acetone. The rest of the sample preparation process for wooden samples was same as for aluminium samples. Schematic and picture of single strap specimen is as shown in Fig. 1.

The specimens were tested in a Universal Testing Machine (Make Blue Star, Model UTE 20) at a crosshead rate of 0.5 mm/min. The UTM was interfaced with a computer for automatic data acquisition and storage. Single strap shear tests were carried out in tensile testing mode. Five specimens were tested for each condition. The gripping length was kept at 30 mm at both ends, while the gripping width was over the whole width of the specimen. The tensile test set-up is as shown in Fig. 2. The load and displacement values were recorded during the tests.

Results and discussions

Surface roughness and shear strength values

Tables 2 and 3 displays the mean surface roughness values R_a and R_z of aluminium and wood adherend samples treated mechanically using emery and sand paper respectively. The surface roughness values of R_a and R_z were taken at nine points over the treated surface area and the representative value was calculated as the average of all nine readings.

The relationship between bonding shear strength and surface roughness of aluminium adherend joints is shown in Fig. 3. Initially, shear strength increased with increasing adherend surface roughness value up to 2.5 µm and then start to decrease, for surface roughness values beyond 2.5 µm. Similar trend of shear strength with respect to surface roughness was found by Tezcan [11] for steel and Loctite 638 adhesive joints under shear

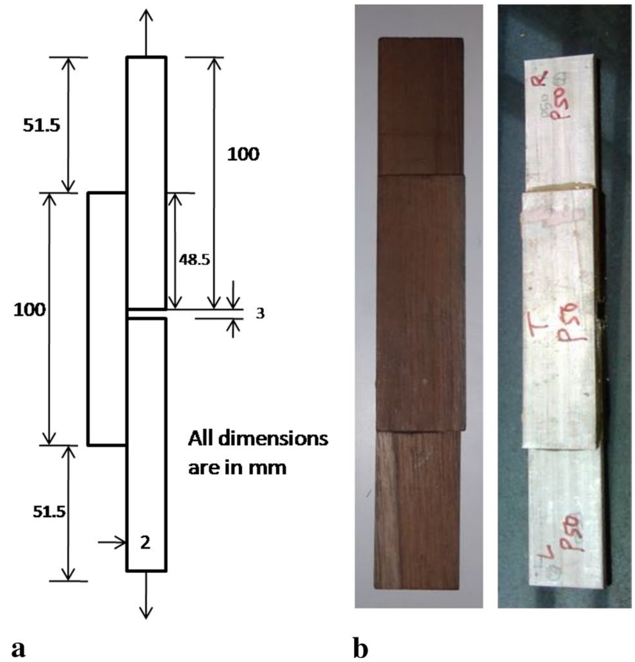

Fig. 1 Schematic and picture of single strap specimen. **a** Schematic specimen configuration. **b** Picture of single strap wood and aluminium joints specimen

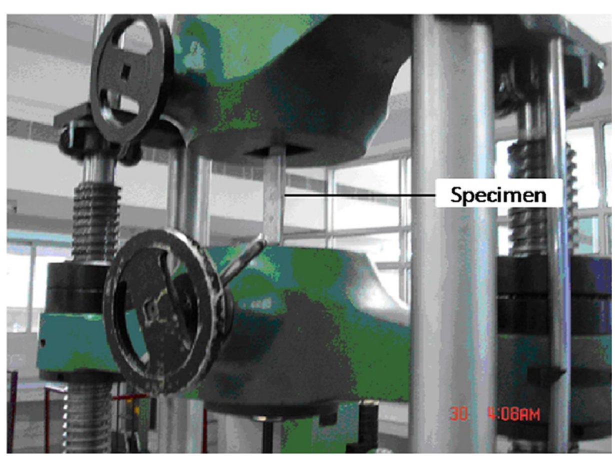

Fig. 2 Tensile test set up

Table 2 Surface roughness value of aluminium adherend

Surface treatment	R_a (μm)	R_z (μm)
No treatment	0.54 ± 0.15	3.75 ± 1.25
Grinding P-120	1.68 ± 0.14	10.27 ± 2.50
Grinding P-50	2.69 ± 0.17	17 ± 1.68
Grinding P-30	3.66 ± 0.13	23.5 ± 2.0

Table 3 Surface roughness value of wood adherend

Surface treatment	R_a (μm)	R_z (μm)
No treatment	1.64 ± 0.20	9.2 ± 1.55
Grinding P-120	2.63 ± 0.19	15.75 ± 2.20
Grinding P-80	3.37 ± 0.18	21.2 ± 1.70
Grinding P-50	4.11 ± 0.22	25.24 ± 1.90

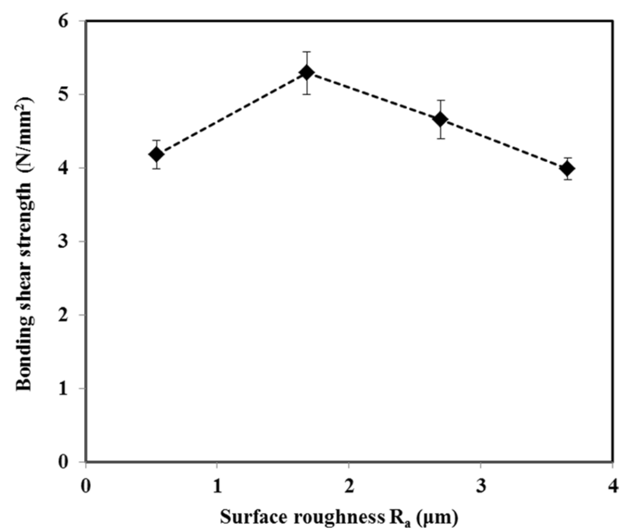

Fig. 3 Relationship between bonding shear strength and surface roughness of aluminium joints

static load. Also Uehara and Sakurai [13] noticed the same variation of bonding strength with respect to adherend surface roughness under both tensile and shear loading.

Significant increase in bonding strength (i.e. 26.70 %) is achieved by maintaining surface roughness values in the range of 1.68 ± 0.14 μm as compared to surface without treatment (0.54 ± 0.15 μm). In this range there would be an optimal point where can get a maximum bonding strength. An increase in surface area, mechanical locking adhesive between micro columns, and modification in the surface chemistry of the adherend are the possible reasons for the improvement in the bond strength at higher surface roughness as compared to the smooth surface [8, 13].Some author [11, 17] observed that an insufficient wetting occur at higher surface roughness and that might be the reason for lower bond strength, when surface roughness value are beyond 2.5 μm (R_a > 2.5 μm).

The relationship between bonding shear strength and surface roughness of wood adherend joints is shown in Fig. 4. It can be seen that the bonding shear strength continuously decreases with increasing the surface roughness of wood adherend joints. The wood adherend with lower surface roughness value has maximum shear strength than the higher surface roughness. 44 % loss in shear strength was found when the adhered surface roughness is in the range of 4.11 ± 0.22 μm as compared to the lower surface roughness 1.64 ± 0.20 μm. The same trend of bonding strength was found by Sulaiman [16] and Murmanis [18].

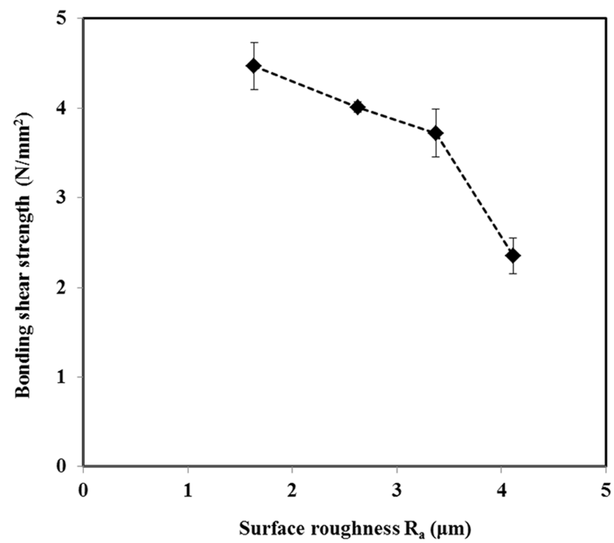

Fig. 4 Relationship between bonding shear strength and surface roughness of wood joints

To conclude, the trend of bonding strength of aluminium and wood adherend are totally different and it depends on the type of adherend materials. The maximum strength can be obtained for the optimum surface roughness value of respective combination of adherend adhesive materials.

Linear regression analysis

The relationship between the surface roughness of aluminium adherend and shear strength of joints are shown in Fig. 5.

The entire experimental data of aluminium adherend joints are divided into two groups. First group consist of original surface of aluminium adherend and varied by the mechanical abrasion using emery paper of P120 grade. The surface roughness of the aluminium adhered was varied by the mechanical abrasion using emery paper of P50 and P30 grade, considered as the second group. The roughness value ranging from 0.41 to 1.78 µm in first group and from 2.59 to 3.74 µm in second group also called lower and higher roughness group respectively. There are 14 pairs of data in the lower roughness group and 13 pairs of data in the higher roughness group.

Equations (1) and (2) were obtained by performing a regression analysis on the experimental data for aluminium adherend joints.

Static shear stress, from 0.41 µm $\leq R_a \leq$ 1.78 µm and 2.59 µm $\leq R_a \leq$ 3.74 µm are,

$$\tau_s = \begin{cases} 1.841 + 8.357 * R_a - 7.674 * R_a^2 + 2.381 * R_a^3 \text{ for } 0.41\mu m \leq R_a \leq 1.78\mu m & (1) \\ 206.7 - 180.8 * R_a + 53.39 * R_a^2 - 5.223 * R_a^3 \text{ for } 2.59\mu m \leq R_a \leq 3.74\mu m & (2) \end{cases}$$

where, τ_s is the shear stress in N/mm^2 and R_a is the surface roughness in µm.

The fitted curves are shown in Fig. 5. The coefficient of correlation estimate R^2 is 0.974 for the first group of data, and 0.84 for the second group. Without performing any additional experiments, Eqs. 1 and 2 can be used to calculate approximate shear stress for the surface roughnessvalues between $R_a = 0.41$ to 1.78 µm and $R_a = 2.59$ to 3.74 µm

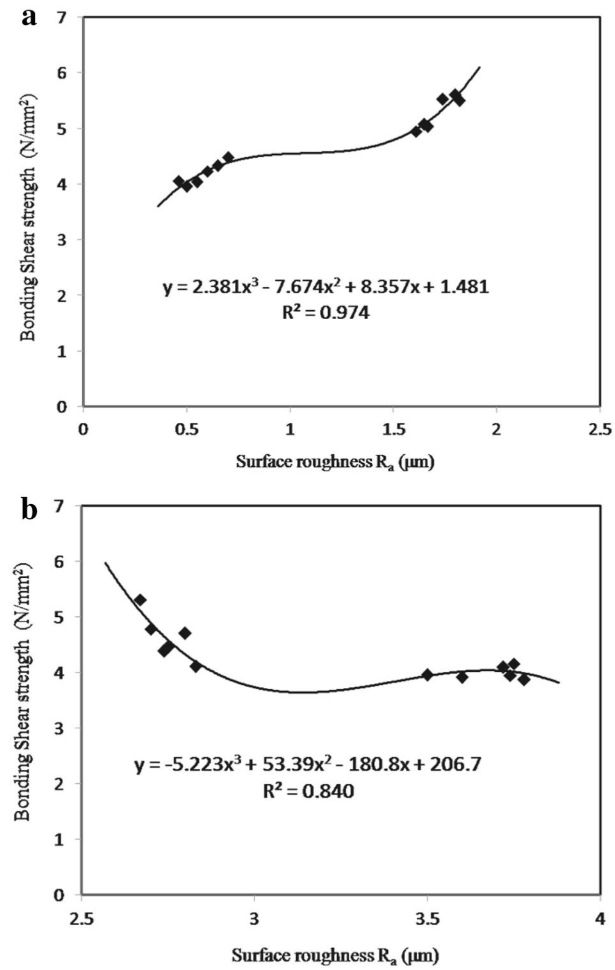

Fig. 5 Curve fitting of bonding shear strength with surface roughness of aluminium adherend joints **a** first group from 0.41 to 1.78 μm roughness values **b** second group from 2.59 to 3.74 μm roughness values

respectively. However, these equations are valid for the specific adherend-adhesive combinations i.e. Aluminium AA6061 and araldite® 2015 adhesive only.

Equation (3) was obtained by performing a regression analysis on the entire experimental set of data for wood adherend joints.

Static shear stress, in the range from 1.64 μm ≤ R_a ≤ 4.11 μm, is,

$$\tau_s = 9.69 + 1.001 * R_a - 8.979 * R_a^2 + 5.948 * R_a^3 - 1.458 * R_a^4 + 0.122 R_a^5 \text{ for } 1.64\ \mu m \le R_a \le 4.11 \quad (3)$$

where, τ_s is the shear stress in N/mm^2 and R_a is the surface roughness in μm.

The fitted curves are shown in Fig. 6. The coefficient of correlation estimate, R^2, is 0.937.

From Fig. 6, it can be seen that the maximum strength was achieved for the lower surface roughness value of wood adherend. As the surface roughness value increased, the bonding strength decrease and vice versa. Bond strength of smooth adherend surface is higher than that of rough one for the wood adhesive bonded joints.

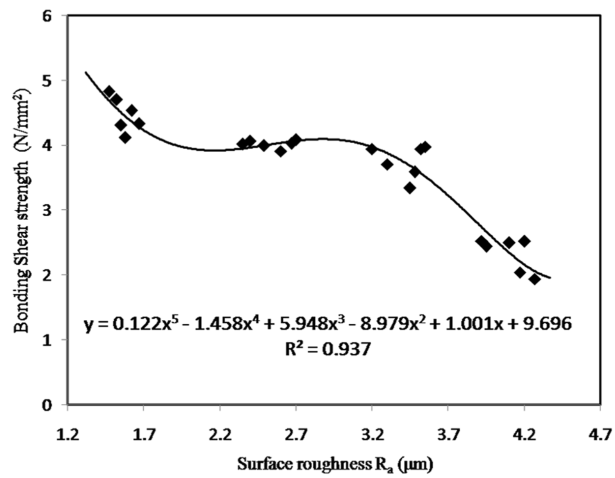

Fig. 6 Curve fitting of bonding shear strength with surface roughness of wood adherend joints

Failure mode

Fractured specimens were visually examined to determine the failure mode. Figure 7 shows the failure surface of the aluminium adhesive joints for all the types of surface treatment specimens. It can be seen that, there was a mixed failure mode for the joints with no surface treatment (low roughness value). Cohesive failure, close to interface, was observed for the joints with surface treatment (P120, P50 and P30). A small contribution of cohesive failure mode (close to interface) could be a possible reason for higher bonding strength at particular surface roughness of adherend.

Figure 8 shows the failure surface of the wood adhesive joints of all the type of surface treatment specimens. Significant variation was observed between the failure surfaces corresponding to the different adherend surface roughness of bonded joints. It can be

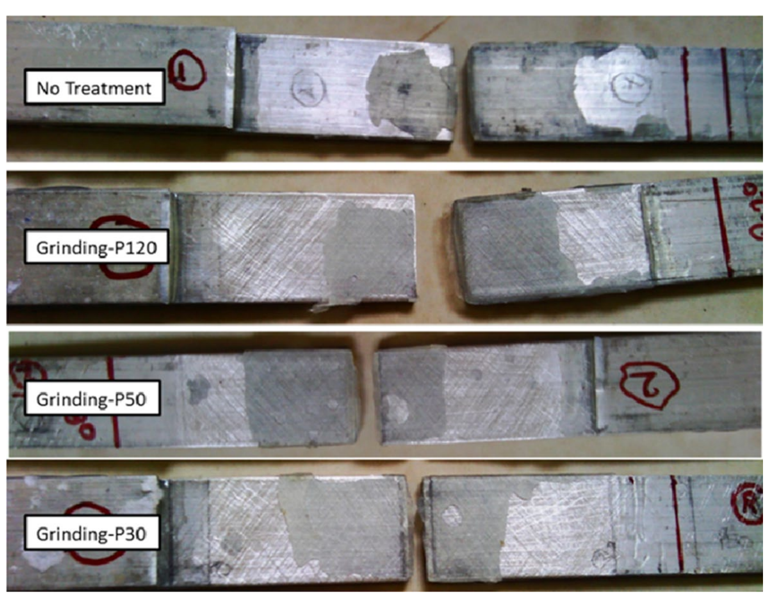

Fig. 7 Failure surface of aluminium adherend bonded joints

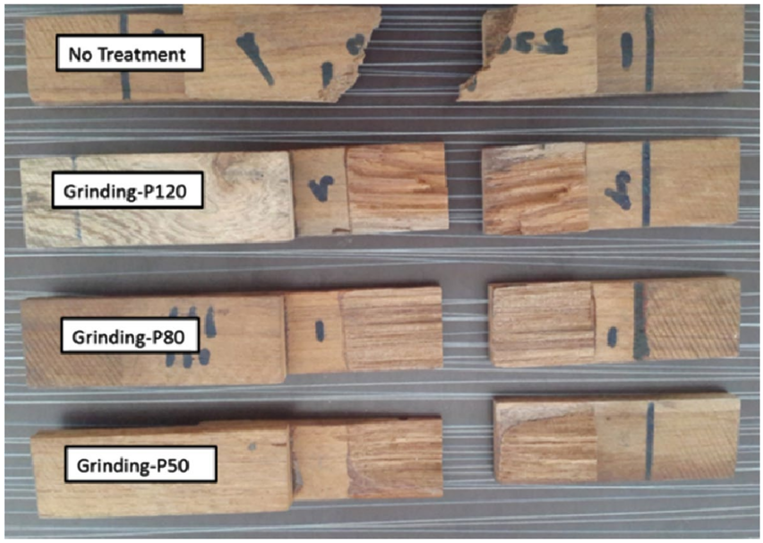

Fig. 8 Failure surface of wood adherend bonded joints

seen that the smooth surface (no treatment) joints failed in adherend failure mode. It implies that the wood adherend is weaker than the adhesive joint strength. As the surface roughness increases (surface treatment, P120, P80 and P50) the failure mode shifted to the partially adherend failure mode and interface failure mode. The contribution of this mixed failure mode changes with increasing the surface roughness value of adhered joints.

Conclusions

Adhesive joints with aluminium and wood adherend were fabricated and tested in order to study the effect of varying surface roughness of adherend on adhesive bond strength.

The findings of the study are as follows:

1. Optimum surface roughness value was found in the range of 1.75–2.5 µm for the maximum bond strength of aluminium adherend joints. The lower bonding strength was obtained for both lower surface roughness ($R_a < 1.68 \pm 0.14$ µm) and very high surface roughness ($R_a > 2.69 \pm 0.17$ µm) also. The adhesive bond strength varies with respect to the surface roughness of adherend.
2. Mixed failure between the adherend and adhesive occurred when the adherend had lower surface (0.54 ± 0.15) and then failure mode partially shift towards the cohesive failure mode close to interface when the surface roughness increases. Cohesive failures along with the mechanical interlocking phenomenon are the possible explanation for the variation in bonding shear strength.
3. The adhesive bond strength decreases continuously with increase in adhered surface roughness of wood adherend. The maximum bond strength was obtained for the smooth wood adherend surface ($R_a = 1.64 \pm 0.25$ µm).
4. Failure mode shifted from adhered failure mode to mixed failure mode as the surface roughness of wood adherend increased from 1.64 to 4.11 µm.

5. The surface roughness parameter must be considered during the design stage of adhesively bonded joints, as the bond strength varied significantly by 30–40 %, between the different surface roughness values.

Authors' contributions

SB (First and corresponding author) was responsible for completing article and guiding to my master student for the experimental work of this paper and discuss results with all authors. AG participated in the experimental works from the purchasing of material to sample preparation and testing of the specimens. NB carried out the data regression analysis and the surface failure analysis of the fracture specimens. MB carried out analysing the failure mode of the fractured specimen, results discussion and great contribute to making final draft of the article. All authors read and approved the final manuscript.

Author details

[1] CEFET/RJ, Federal Center of Technological Education in Rio de Janeiro, Av-Maracanã, 229, Riode Janeiro, RJ 20271-110, Brazil. [2] Mechanical Engineering Department, SIT, Lavale, Pune 412115, India. [3] 3DPLM SoftwareSolution Ltd, Pune 411057, India.

Competing interests

The authors declare that they have no competing interests.

Received: 24 November 2015 Accepted: 8 December 2015
Published online: 14 December 2015

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