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Influence of Adherend Surface Roughness on the Adhesive Bond Strength

Abstract

Surface treatment of the adherends prior to adhesive bonding plays an important role in the enhancing of strength and durability of bonded joints. In this work, an investigation on effect of adherend surface roughness on adhesive bond strength was performed. Single strap joints with different adherends (mild steel and aluminium) bonded with an epoxy resin (Araldite® 2015) were tested. The adherend surface was treated by mechanical abrasion process using an emery paper. Contact angle measurement and SEM analysis to understand the wettability and the failure mechanism of the joints were performed. It was found that an optimum surface roughness exists for a maximum bonding strength and the roughness range depends on the adherend material. The joint strength changes are associated not only simply by the increased bonding area, surface texture or mechanical interlocking, but also by the chemical characteristics of the surface and the chemical bond between them.

Keywords

Surface roughness; adhesive bond strength; adherend material; contact angle.

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1 INTRODUCTION

The adhesive bond joint strength depends on the mechanical and the chemical properties of adherend and adhesive material. Therefore the characteristics of bonding area have a great importance in industrial application for achieving maximum strength. A number of researchers have examined the effect of different parameters on the strength and durability of adhesive joints. These parameters are: the type of adhesive (Nunes et al., 2015), the type of adherend (Goudardzi and Khedmati, 2015), the surface preparation (Budhe et al., 2015) and the bondline thickness (Reza et al., 2014; Banea et al., 2015), among others.

Surface preparation is one of the important parameters which is directly related to the quality of the bonded joint. In order to get a strong and durable bonded joint, a surface treatment of adherends should ensure the following aspects: removal of all contaminants (lubricants, dusts, loose corrosion layers, micro-organisms) from the surfaces (da silva et al., 2009), good surface wettability (Encinas et al., 2012; Sedev et al., 2014), surface energy (Guzanova et al., 2014; Islam et al., 2014), good activation of surfaces of elements being bonded (Encinas e al., 2014) etc. There are different chemical and physical surface treatments available, but proper selection of surface treatment is very important (Rotella et al., 2016; Williams et al., 2014; Maressa et al., 2015).

Mechanical abrasion is one of the most widely used surface treatment. Different surface pattern and roughness are easily obtained by the mechanical abrasion process. Many researchers (Baburaj et al., 2007; Azari e al.,2010; Hunter et al., 2012; De Barros et al., 2015) focused on the effect of surface roughness on the bonded joint strength under different loading condition. Tezcan et al. (2003) studied the effect of surface roughness on the adhesive bond strength under static and dynamic loading condition using a cylindrical specimen of steel adherend and Loctite 638 adhesive. They found maximum bond strength, when the adherend surface roughness was in the range of 1.5 to 2.5 μm. Shahid and Hashim (2001) studied the effect of surface roughness on the cleavage joint strength using grit-blasting and diamond polishing roughness method. They observed diamond polishing produces less strength than the grit-blasting method and rough surface produces less tensile stresses than the polished surface. Uehara et al. (2002) also found that an optimum surface roughness value exists for the maximum tensile strength. In the adhesive bonded joint, the cleaning of adherend surface is also an important factor which eliminates dirt and oils from the surface and improves the strength of the joints. Most of the researchers (Zielecki et al., 2013; Madolfino et al., 2015) used acetone as a cleaning agent because it gives very low chemical reaction in adherend materials.

A significant difference is usually observed in adhesive bonded joint strength with variation in adherend surface roughness. However, there are other parameters responsible for the increment in joint strength, such as adherend-adhesive material, bondline thickness, loading conditions, etc. There is no generalized strength trend with surface roughness, therefore it is of interest to investigate the effect of different adherend surface roughness on the adhesive bond strength.

The main objective of this study is to investigate the effect of different surface roughness for aluminium and mild steel adherend on the adhesive bond strength. Contact angle measurement was performed to study the wettability as a function of surface roughness. Finally, a SEM analysis was also performed to understand the failure mechanism.

2 EXPERIMENTAL DETAILS

2.1 Materials

Aluminium AA6063 and mild steel AISI1045 were used as adherends in this study. Aluminium and mild steel plates were cut by shearing machine at required dimension of 100x25x3 mm. A bi-component structural epoxy adhesive Araldite® 2015 (supplied by Huntsman International (India)

Private Limited) was selected for this study. Mechanical properties of Araldite® 2015 are summarised in table 1 (da silva et al., 2009, Campilho et al., 2013). Chemical composition and mechanical properties of aluminium AA6063 and mild steel AISI1045 are shown in table 2 and table 3 (supplier data).

Property	Araldite® 2015
Young's modulus, E (GPa)	1.85±0.21
Poisson's ration, ν	0.33
Shear modulus (GPa)	0.56±0.21
Tensile yield strength (MPa)	12.63±0.61
Tensile failure strength (MPa)	21.63±1.61
Shear yield strength (MPa)	14.6±1.3
Shear failure strength (MPa)	17.9±1.8

Table 1: Mechanical properties of adhesive Araldite® 2015 (da silva et al., 2009, Campilho et al., 2013)

Chemical composition (%)								Mechanical properties		
Fe	Mg	Si	Cu	Zn	Cr	Ti	Al	Ultimate tensile strength (Mpa)	Yiels strength (MPa)	Elongation (%)
0.3	0.9	0.6	0.1	0.1	0.1	0.1	Balance	241	214	12

Table 2: Chemical composition and mechanical properties of aluminium AA6063 adherend.

Chemical composition (%)					Mechanical properties		
Fe	Mn	P	S	C	Ultimate tensile strength (Mpa)	Yiels strength (MPa)	Elongation (%)
98.98	0.9	0.04	0.05	0.5	565	310	16

Table 3: Chemical composition and mechanical properties of mild steel AISI 1045 adherend.

2.2 Surface Preparation

Two kinds of adherend surface were used, one abraded using an emery paper and another type without abraded surface. Three different grades of emery paper, P50, P80 and P120 were used for the different surface roughness values and the flat plate without abraded surface was considered as a one grade. The surface roughness pattern applied to the adherend was 0°, 90° and ±45° orientation (relative to loading direction). Figure 1 shows the surface roughness pattern used for both aluminum and mild steel adherend.

Two roughness parameters: the average surface roughness (R_a) and the maximum surface roughness (maximum height of profile, R_z) were used to evaluate the surface quality of the specimens. Surface roughness values, R_a and R_z were measured using a profilometer (Mitutoyo-SJ210, Japan) for both abraded and non abraded samples. The cut-off length 4 mm was selected for the measurement and the profilometer measuring range was 0.01-10.0 μm. The surface roughness measurements were performed in different areas, along two different directions (longitudinal and transverse). The measured surface roughness values, R_a and R_z of aluminium and mild steel adherend are given in table 4 and 5, respectively.

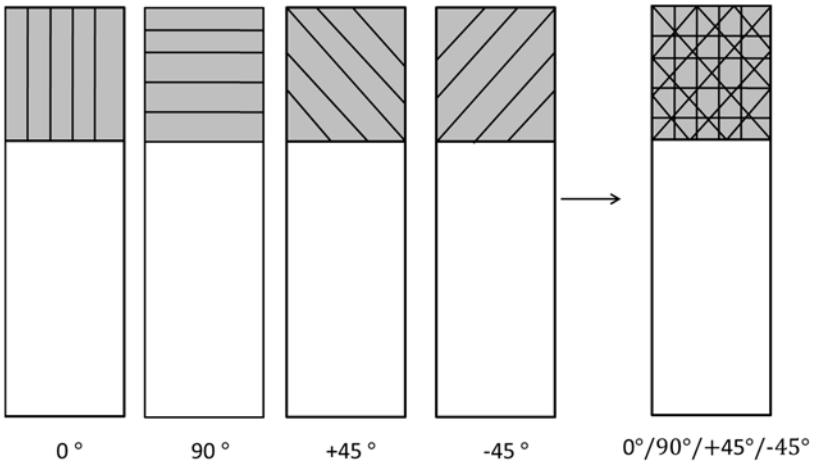


Figure 1: Geometry of surface roughness pattern (0°/90°/+45°/-45°).

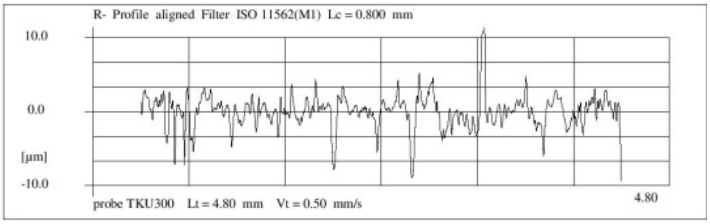
Surface treatment	R_a (μm)	R_Z (μm)
Non abraded	1.55± 0.15	13.99± 2.05
Abraded by P120	2.05± 0.19	13.45± 1.75
Abraded by P80	2.92±0.20	23.27± 2.10
Abraded by P50	3.46±0.17	22.73± 1.65

Table 4: Surface roughness measurements R_a and R_z values of aluminium adherend after surface treatment.

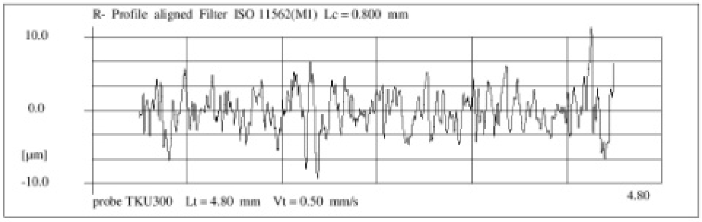
Surface treatment	R_a (μm)	R_Z (μm)
Non abraded	1.83± 0.12	12.75± 1.95
Abraded by P120	1.98± 0.10	13.42± 2.15
Abraded by P80	2.60± 0.16	16.60± 1.45
Abraded by P50	3.24± 0.19	17.45± 1.80

Table 5: Surface roughness measurements R_a and R_z values of mild steel adherend after surface treatment.

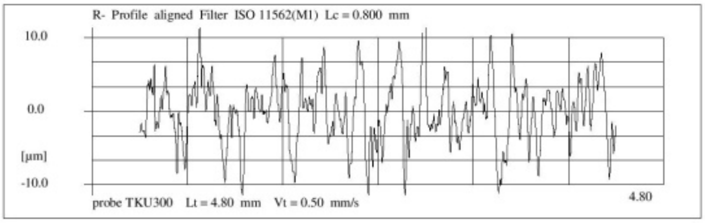
Surface roughness tester (Hommelwerke Model T8000) was used to measure the 2D surface roughness profile of both aluminium and mild steel adherends. ISO 11562 (M1) filter was used with a transverse length of 4.80 mm and cut-off length of 0.800 mm. The measuring range of the surface roughness tester was a 800 μm, while the speed was 0.50 mm/s. 2D surface profile of both aluminium and mild steel adherends is as shown in fig.2 and fig.3.



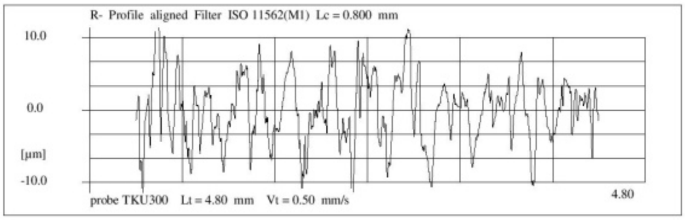
a) Non abraded



b) Abraded by P120



c) Abraded by P80

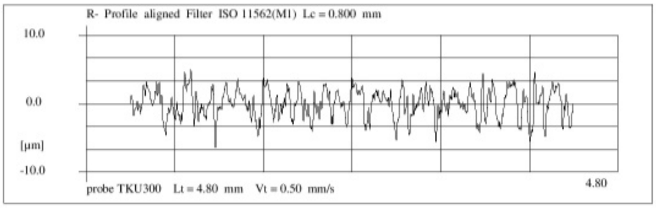


d) Abraded by P50

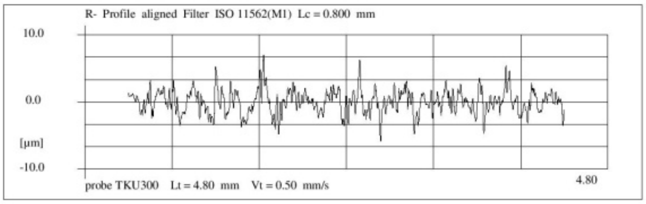
Figure 2: 2D surface roughness profile of aluminium adherends with different surface treatment.

2.3 Contact Angle Measurement

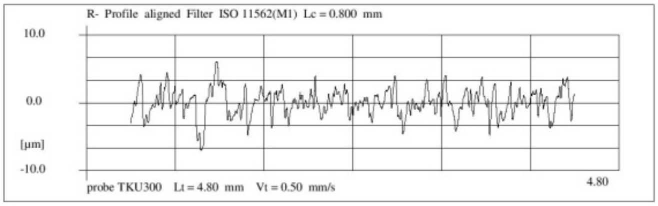
The wetting characteristic of all types of the adherend surface (different surface roughness) was determined using a contact angle. Kruss Drop Shape Analyzer (DSA25E) equipment was used to measure the contact angle (Fig.4). In order to measure the contact angle, a 1 ml drop of epoxy resin Araldite® 2015 was deposited on the adherend surface with a disposable micro-syringe. A minimum of three contact angle tests was recorded in different surface area to obtain an average result and also cross verification of surface uniformity. The complete instrument set-up for contact angle measurement is shown in Fig.4.



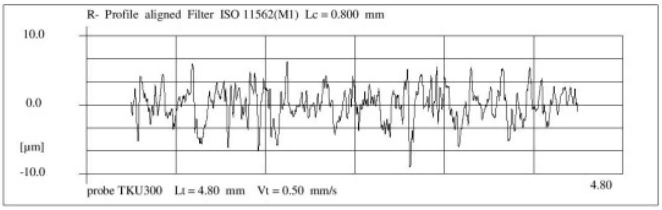
a) Non abraded



b) Abraded by P120



c) Abraded by P80



d) Abraded by P50

Figure 3: 2D surface roughness profile of mild steel adherends with different surface treatment.

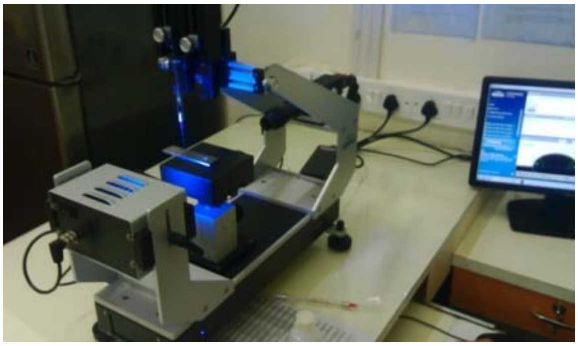


Figure 4: Experimental set up for contact angle measurements (Kruss Drop Shape Analyzer).

2.4 Sample Preparation

A single strap joint geometry was used for the experiment (fig.5). The bonding surface area was cleaned with acetone before the application of the adhesive. The adhesive was applied on the adherend surface and spread over it with a spatula. The adherends were then bonded by applying constant pressure on the specimen upto 48 hrs. The joints were cured at room temperature for 48 hrs. The adhesive thickness was 0.35±0.05 mm.

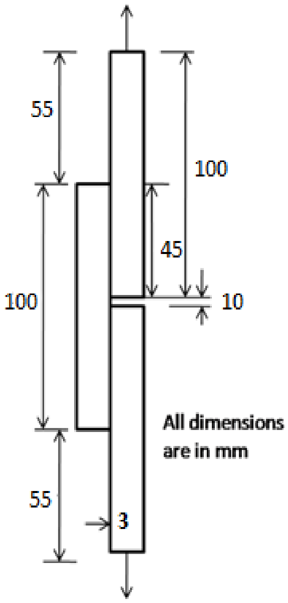


Figure 5: Single strap joint configuration.

2.5 Test Method

The single strap specimens were tested using an universal testing machine (Fine Spavy Associates and Engineering Pvt. Ltd., India) under monotonic loading at room temperature with a cross-head speed of 0.5 mm/min. Five specimens were tested for each condition at room temperature. The gripping length was kept at 30 mm at both ends, while the gripping width was over the whole width of the specimen. Load-displacement values were recorded.

3 RESULTS AND DISCUSSIONS

3.1 Effect of Surface Roughness on Contact Angle (Wettability)

As it can be seen from fig. 6 and fig. 7, the contact angle increases continuously with increasing surface roughness. However, a negligible increment was observed at lower surface roughness range (i.e between the non abraded adherend surface and adherend abraded by P120) in both adherend type joints. The contact angle increases from 88° to 112° and 85° to 107° for aluminium and mild steel adherends, respectively, when abraded by P50 compared to P120. This high increment in contact angle with the surface roughness values (P120 and P80) in both adherend type lead to lower wettability which make a barrier for adhesive spreading on the surface (Barsellino et al., 2008). It means, the adhesive does not penetrate well completely into asperities and consequently, the interface between liquid and solid is not continuous over the overlap area. This reduces the effective bond area and leads to interfacial failure instead of cohesive failure of adhesive as noticed by Hitchcock et al. (1981).

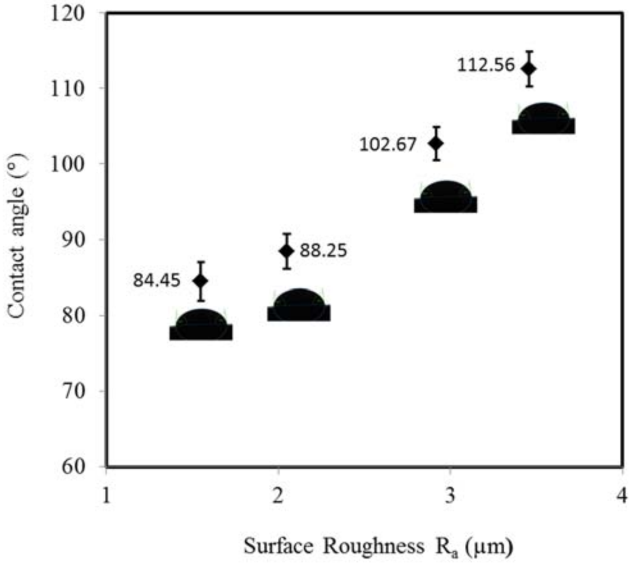


Figure 6: Contact angle as a function of surface roughness of aluminium adherend.

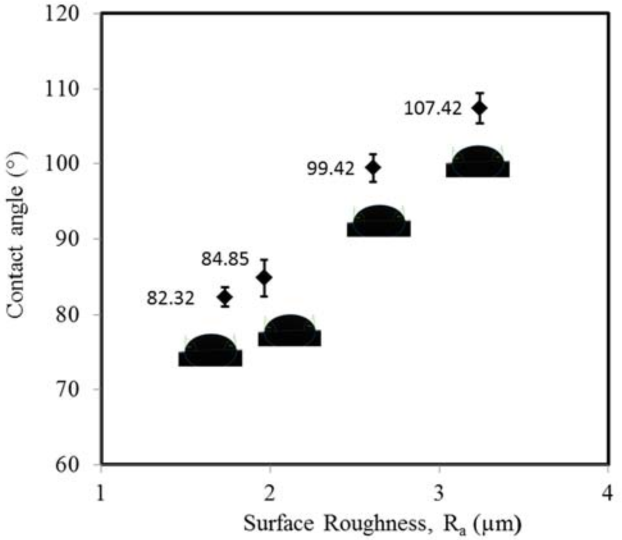


Figure 7: Contact angle as a function of surface roughness of mild steel adherend.

3.2 Effect of Surface Roughness on Shear Strength

Table 6 and 7 shows the shear strength with respect to surface roughness value of aluminium and mild steel adherends. Aluminium adherend having surface roughness value of 1.55±0.15 µm (non abraded surface) and their corresponding bond strength 3.54 N/mm2 was taken as reference value for comparison. From Table 6 it can be seen that the shear strength increases with increasing surface roughness of the aluminium adherend compared to the non abraded adherend surface. A maximum of 40% increment in shear strength was observed when the adherent surface roughness was in the range of 2.05±0.19 µm as compared to the non abraded adherend surface (1.55± 0.15µm). A high surface roughness of the adherend material was not proven to provide significant improve in terms of shear strength of the joints.

The same trend of shear strength joints with respect to adherend surface roughness was observed for the mild steel adherend bonded joints (table. 7). A continuous increase in shear strength was observed up to a maximum surface roughness of 3.24±0.19 µm as compared to the non abraded adherend joints. After adherend surface roughness of Ra=1.98±0.10 (P120), the percentage increments in joint strength is not significant, but still is higher when compared to non-abraded adherend joints. Almost 60% gain in shear strength is observed when the adherend surface roughness is 1.98±0.10 µm.

Surface treatment	Roughness, R_a (µm)	Shear strength (N/mm^2)	Increase in shear strength
Non abraded	1.55± 0.15	3.54	
Abraded by P120	2.05± 0.19	4.97	40.39
Abraded by P80	2.92±0.20	3.95	11.58
Abraded by P50	3.46±0.17	3.70	4.52

Table 6: Shear strength with respect to surface roughness value of aluminum adherends joints.

Surface treatment	Roughness, R_a (µm)	Shear strength (N/mm^2)	Increase in shear strength
Non abraded	1.63± 0.12	4.24	
Abraded by P120	1.98± 0.10	6.78	59.90
Abraded by P80	2.60±0.16	6.15	45.04
Abraded by P50	3.24±0.19	6.03	42.21

Table 7: Shear strength with respect to surface roughness value of mild steel adherends joints.

Figure 8 shows the shear strength with respect to the adherend surface roughness of both adherend bonded joints. It is clearly seen that both the alumimum and mild steel adherend joints follow the same shear strength trend with only the difference in the magnitude of strength. Almost, 40-50% shear strength difference was observed between the mild steel and aluminium adherend joints in all ranges of surface roughness, except at lower roughness value. Both the adherend joints showed an increase in shear strength with an increase in surface roughness and then decrement in strength. These results are in agreement with previous research (Tezcan et al.,2003; Pereira et al., 2012; Saleema et al., 2012).

Increase of bonding area, mechanical interlocking between surface modification and micro-columns of the adherends are the possible reasons for the improvement in strength at initial level. Howecer, but at the higher surface roughness this is not valid. From the contact angle study, it was found that higher contact angle at the higher surface roughness as compared to P120 adherend surface which lead to lower wettability. This might be the reason for lower shear strength at high roughness value even though the bonding area is higher. A maximum shear strength can be obtained over the optimum surface roughness value for a particular adherend-adhesive bonded joints. However, a simple correlation with the surface roughness is not sufficient to predict the joint performance, as there are other parameters responsible for the increment in strength (Spagiari and Dragoni, 2013).

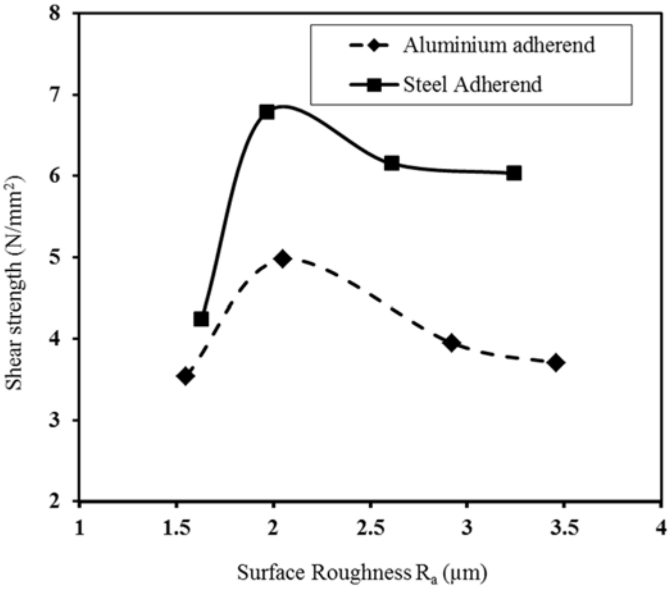
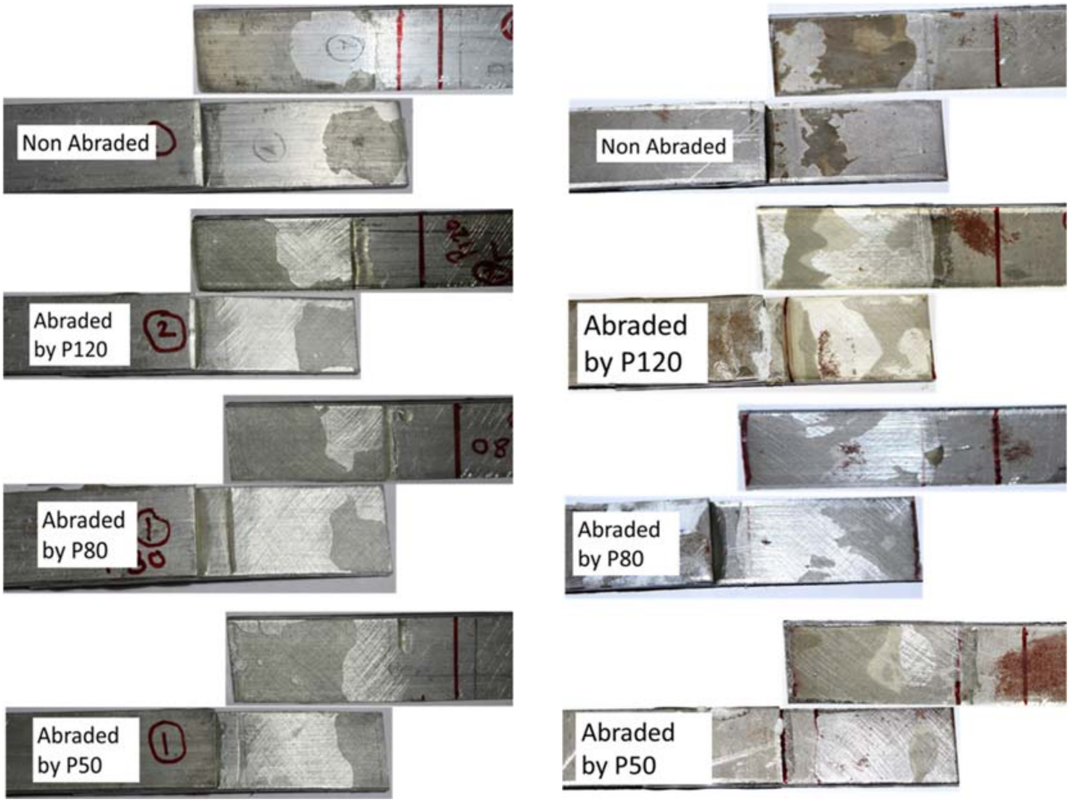


Figure 8: Shear strength with respect to the adherend surface roughness of aluminium and mild steel adherend joints.

3.3 Examination of Fracture Surface

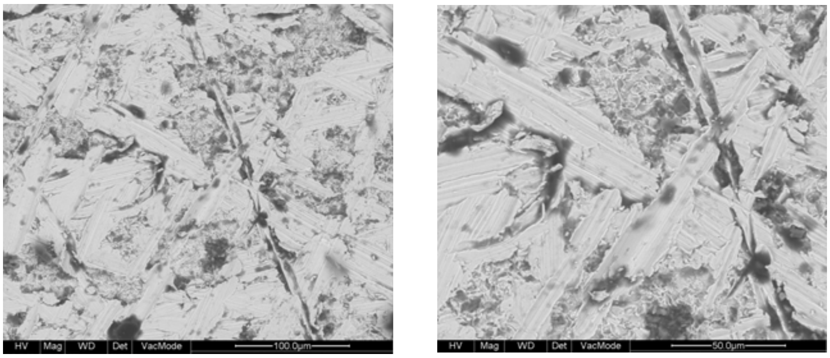
The failure mode of the specimens was visually examined after testing and can be seen in fig. 9. Upon visual examination, all the joints prepared by different surface treatments have shown dominantly interface failure. This is in the same line of findings by Hitchcock et al. (1981). They concluded that an increasing surface roughness usually reduce the wettability of the surfaces. This phenomenon might be the reason for interfacial failure in both adhered type bonded joints.



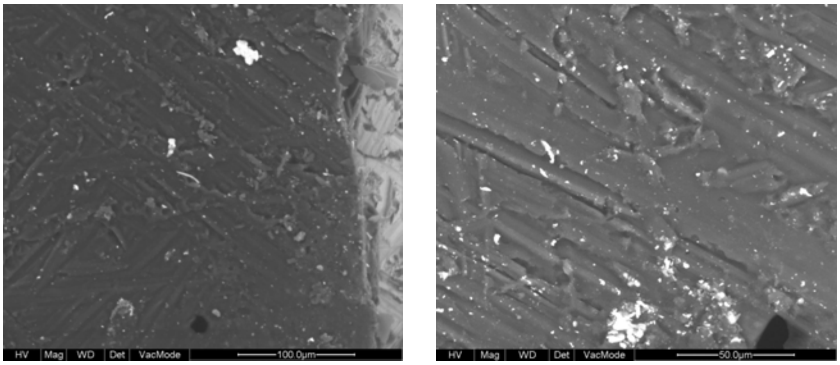
(a) Aluminium adherends bonded joints (b) mild steel bonded joints

Figure 9: Failure surface of Aluminium adherends and mild steel bonded joints.

A Scanning Electron Microscopy (SEM) analysis was carried out with the joints having a higher failure load in order to better understand the failure mechanism. Figure 10 and 11 show a typical SEM micrograph resulting from a mild steel adherend and aluminium adherend joints with mechanical abrasion by P120 emery paper.



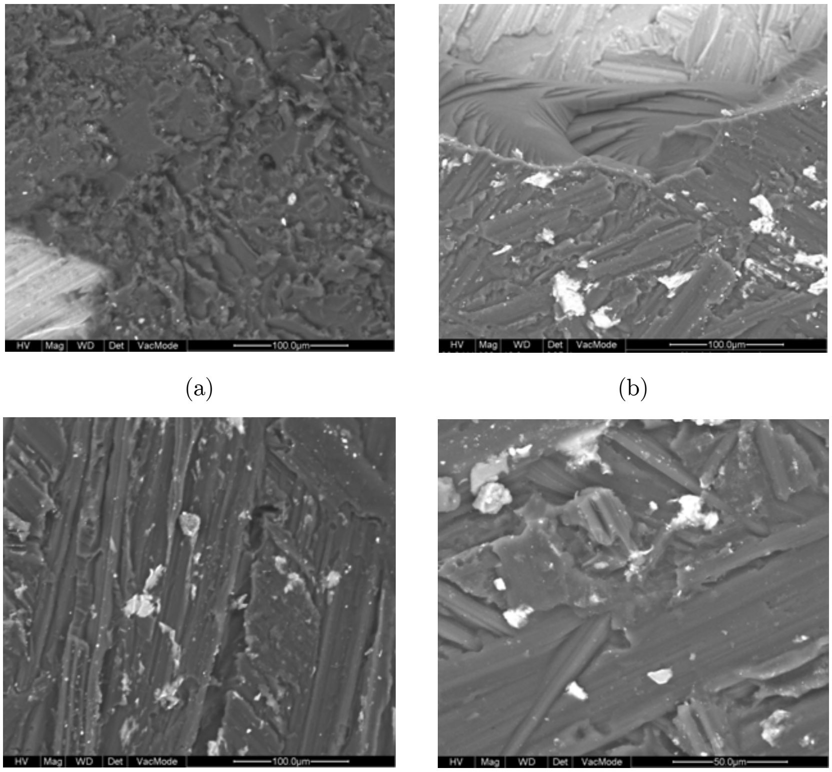
(a) (b)



(c) (d)

Figure 10: SEM image of fracture surface of both panels, (upper plate image on top and lower plate image at bottom) joints with mild steel adherend.

From the SEM images, shear yielding bands can be observed, which indicate plastic deformation (particularly evident from the fig. 10b). The adhesive remains on the lower adherend surface, as shown in fig. 10c,d, indicating that cohesive failure of the adhesive occurred in some regions.



(a) (b)

(c) (d)

Figure 11: SEM image of fracture surface of both panels, (upper plate image on top and lower plate image at bottom) joints with aluminium adherend.

The fracture surface of aluminium adhered joints specimen, fig. 11a, shows a rough adhesive surface, which indicates adhesive plastic deformation. Fig. 11c presents an adhesive left on the adherend surface, close to the interface layer. Both joints specimen show evidence of adhesive ductility, regions of cohesive failure and also interface failure mode.

4 CONCLUSIONS

In this work, the effect of adherend surface roughness on adhesive bond strength was investigated. Single strap joints with different adherends (i.e. mild steel and aluminium) were tested.

The following conlusions can be drawn:

1) There is an optimum surface roughness for maximum strength in both aluminum and steel adherend joints. Examination of fractured surfaces (SEM) after testing showed an evidence of adhesive deformation for the joints at higher failure load.
2) The strength variations with respect to the surface roughness follow the same trend (initially increases and then decreases with roughness) as a function of material. However, a large difference in magnitude of the shear strength between aluminium and mild steel adherend joints was observed. It implies that there is a strong dependence of adherend material on the adhesive bond strength along with the surface roughness factor.
3) Contact angle increases continuously with an increasing surface roughness compared to the non-abraded specimen. The shear strength of all treated surface joints is higher than the non abraded adherend joints, despite the higher contact angle (lower wettability). It implies that these increments in shear strength are not supported by contact angle (wettability) phenomenon.

The above results indicate that the shear strength associated with the different adherend surface roughness cannot be explained only by increased roughness characteristics, such as mechanical interlocking, surface texture and increased bonding area. An understanding of the chemical bond characteristics between the adhesive and adherend material before an application is also essential. Even though surface roughness is an important parameter for joints strength, the proper selection of adherend-adhesive material combination should not be ignored for maximum performance of adhesive bonded joints.

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