Khan *et al. Appl Adhes Sci (2016) 4:21*
DOI 10.1186/s40563-016-0077-1

Applied Adhesion Science

RESEARCH

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Effect of oxidation and surface roughness on the shear strength of single-lap-joint adhesively bonded metal specimens by tension loading

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Abstract

An experimental investigation was performed to study the effect of surface roughness and oxidation on the shear strength of single-lap-joints of AA6061, AA7075 aluminum alloys and an AISI 1080 steel alloy bonded with two different epoxy adhesives. An optimum surface roughness that provided the maximum shear strength was obtained for all the alloys at room temperature. The variation of the shear stress due to the different heat treatment temperatures revealed that the oxides developed on the alloy surfaces adversely affected the adhesive shear strength. The bulk concentration of magnesium of the aluminum alloys were also observed to affect the adhesive shear strength of the joints.

Keywords: Adhesive bonding, Aluminum alloys, Steel, Surface roughness, Adhesion strength, Oxidation

Background

Adhesives are known to have been extensively used for several decades in the aerospace industry for joining of structural load-bearing components [1, 2]. Their application to the automotive industry has been inspired by the desire for cheaper and lighter products [1]. The consideration of sealants and high strength adhesives as replacements for welding, which has been the traditional major automotive joining method to bond load bearing structural components, is also due to the limits observed with welding (such as in the joining of aluminum) and their high joint stiffness and superior fatigue performance [1–3]. Although adhesive bonding is particularly effective in joining thin metals and composites, the structural performance of the adhesive can be judged by its tendency to debond or fracture [4]. Debonding is caused by high interface adhesive stresses existing at free or terminating ends of adhesive layers, while fracture in the adhesive or the adhesive-adherend interface has been linked to the presence of shear and peel stresses in the adhesive layer [4]. However, a strong bonding joint is produced by the adhesive layer when it is thin and continuous despite the strength of the adhesive been much lower than the adhered metals [3]. The nature of the adhesive bond is dependent on the atomic arrangement, chemical properties, constitution and diffusivity of the constituent elements [3]. Therefore the properties of the interface between the different adherends must possess specific properties to achieve acceptable joints [3]. Good adhesion between adherends, i.e., the shear strength of the adhesive bond, would therefore be heavily dependent on the pre-treatment of the adhered surfaces, the choice of adhesives, the design of the joint and the service condition as well as the adhesive application process [3, 5, 6]. Surface pre-treatment involves the removing of contaminants as well as chemically activating and modifying the surfaces to facilitate the chemical bond between the surfaces, initiate resistance to hydration and other environmental deterioration agents [3, 6].

A typical test used to assess the shear strength of adhesive bonds is the single-lap shear tests [5, 7]. The shear strength of these bonds is also known to be altered by environmental changes, changes in metal specimens and adhesive, and changes in the joints in any manner. Early research by Brewis et al. [8] on the effect of humility on the durability of aluminum-epoxide joints revealed that joints formed with this adhesive were stable up to 1008 h at 50 °C and relative humidity's between 23 and 100%, after which time, some weakening was observed. Similarly, Butkus [9] reported the reduction in strength and toughness of epoxy adhesives on exposure to high temperature and humidity. However, Su et al. [10] observed that some adhesives were resistant to environmental effects. They suggested that exposure to the natural environment represented the severest test conditions, and that the performance of these adhesives were reduced significantly in the natural environment as compared to other environmental conditions, such as high humidity [10]. They also proposed that the fatigue performance of some adhesives could possibly be improved with age [10]. Datla et al. [11] studied the mixed-mode fatigue behaviour of degraded toughened epoxy-aluminum adhesive joints and revealed that the fatigue threshold strain energy release rate was decreased, while the crack growth rate increased with aging time in constant humidity environments. Also, they observed the degradation of joints and crack growth rates increased in relation to the aging temperature increase. The adhesive modulus is another factor that has been reported to possess considerable influence on the shear stress. It has been observed that the maximum peel stress, shear stress, and longitudinal stress in a single-lap-joint is directly proportional to the adhesive modulus, however, these parameters are inversely proportional to the adherend modulus [12].

Da Silva et al. [13] studied the effect of material, geometry, surface treatment, and environment as variables that would influence the strength of single-lap-joints in long term. They concluded that lap shear strength was directly proportional to the overlap, the adherend yield strength, and the adhesive toughness at relatively lower applied stresses and inversely proportional to the adhesive thickness, the adherend thickness, and the adhesive toughness at higher stresses [13]. Subsequent studies on the effect of adhesive thickness and toughness on the lap shear strength revealed that decreasing the adhesive thickness and increasing the adhesive toughness increased the lap shear strength [14]. Studies on the influence of some geometrical parameters on the stress concentrations of the single-lap-joints revealed that a significant concentration of stress can exist throughout the thickness of the adhesive [15]. Therefore, detailed analysis of the stress distribution in the adhesive was suggested as being preferable to the simplified analysis of the average stress state through the joint, as it would prove a more ideal analysis [15].

Shorter bond lengths, and stiffer laminate adherends have been observed to improve the fatigue strength of bonded composites [16]. However, hot and wet environmental exposure has been reported to adversely affect the fracture toughness of double cantilever beam (DCB) and end-notched flexure (ENF) aluminum/FM 73/boron-epoxy bonded joints [17]. While oxidation has been shown to induce only superficial damage in constant temperature environments, when the temperature is varied cracks can developed on the sample edges, eventually propagating towards the core [18].

As adhesive bonding becomes one of the main joining methods for aluminum alloys with its introduction into the aerospace and transport industries, research into the adhesive bonded aluminum joints continues to grow [6, 19]. It has been shown that the surface roughness induced on the aluminum alloy by abrasive grinding has a pronounced effect on the adhesive strength [6]. The complex relationship between adhesion and the surface roughness of the adherend has been noted by several researchers, who have reported an optimum surface roughness and surface conditions for maximum adhesive strength [19, 20]. While oxides formed on the aluminum alloy surface due to magnesium diffusion have been reported to be detrimental to the bonding of adhesives, certain concentrations of magnesium in aluminum alloys have been reported to increase the bond strength [21–24]. The effect of the bulk concentration of magnesium in Al–Mg alloys on the adhesion strength has also been another topic of concern for researchers [24].

As the surface quality of the adherend has a strong influence on the adhesive strength, it is therefore practical that oxidation and the surface roughness of specimens are two factors that can influence the behaviour of single-lap-joint adhesively bonded metal. In this paper, the effect of these two factors, oxidation and roughness of the specimens, on shear strength of single-lap-joint adhesively bonded metal specimens by tension loading are investigated, and the obtained results from different cases are studied and compared. While similar work has been carried out, this paper concentrates on the performance of automobile alloys, in particular magnesium containing aluminum alloys. The aim was to investigate the influence of the adhesive type and alloy composition on the optimum surface condition for maximum bond strength. The effect of bulk magnesium concentration of aluminum alloys at various stages of oxidation and the influence of oxides produced on the alloy surface on bond strength were also of interest. A steel alloy was used as a baseline to determine dependency of the alloy type on the effect of surface roughness and surface oxidation.

Experimental procedure

Materials

There were two adhesives employed in this study, A1, a polyamide-epoxy and A2, an epichlorohydrin-epoxy. The mechanical properties of these adhesives are given in Table 1. Each adhesive was applied independently to each set of the metal alloy samples. The metal samples, possessing varying surfaces conditions, were bonded in the geometry of a basic single-lap-joint as shown in Fig. 1. The adherend alloys, AISI 1080 steel, AA6061 and AA7075 aluminum alloys, had dimensions also depicted in Fig. 1. The surfaces of a set of each of the adherend alloys were ground with 60, 120, 240, and 340 grade SiC type emery papers and their surface roughness analyzed with a WYKO NT1100 optical interferometer. The surface roughness values were obtained from nine different

Table 1 Mechanical properties of the A1 and A2 adhesives

Mechanical properties	A1	A2
Cure temperature (℃)	175	180
Cure time (min)	60	30
Tensile strength (Mpa)	37	29
Density (g/cm^3)	0.30	1.20

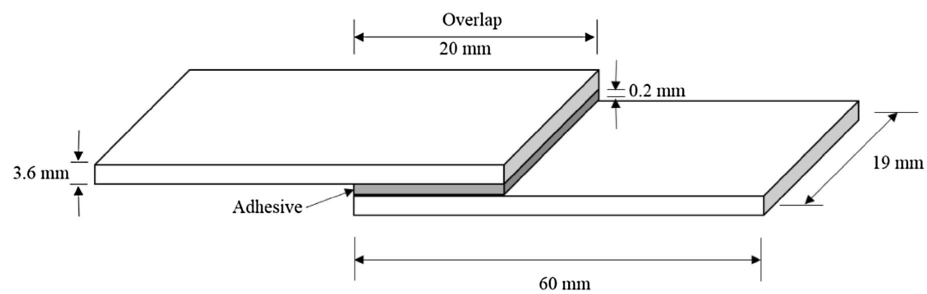

Fig. 1 Geometry and dimensions of the single-lap-jointed specimen

points over the each ground adherend surface and the average surface roughness values displayed in Table 2. This was done to investigate the effect of surface roughness on the bond joint strength. Three single-lap-joints were tested at each surface roughness for each of the alloys. The adherend surfaces then carefully cleaned with acetone after grinding to remove any surface contaminants before the adhesives were applied. The rest of the metal specimens were heated in a furnace for the duration of 60 mins at the temperatures of 100, 200, and 300 °C prior to the application of the adhesives to study the effect of surface oxidation. This section of the study was performed for a single roughness derived from grinding with the 240 grade SiC type emery paper. Three single-lap-joints were again tested at each temperature for each of the alloys.

Table 2 Average surface roughness (R_a) values of the alloys ground with the corresponding SiC type emery papers

Surface treatment	R_a (μm)	Alloy
Grinding 60 grit SiC	1.88 ± 0.52	AA6061
	1.88 ± 0.52	AA7075
	1.45 ± 0.52	AISI 1080
Grinding 120 grit SiC	1.01 ± 0.15	AA6061
	1.01 ± 0.15	AA7075
	0.86 ± 0.07	AISI 1080
Grinding 240 grit SiC	0.83 ± 0.05	AA6061
	0.83 ± 0.05	AA7075
	0.62 ± 0.09	AISI 1080
Grinding 320 grit SiC	0.6 ± 0.07	AA6061
	0.6 ± 0.07	AA7075
	0.47 ± 0.05	AISI 1080

Test procedure

Tensile tests performed on the bonded single joint sample was carried out with a MTS universal testing machine at a test speed of 0.01 mm/sec. The specimens were place in the jaws of MTS Universal testing machine and carefully tightened in order to ensure that the specimen stayed perfectly vertical as any inclination would lead to the bending moment on the specimen and the pure shear strength would be compromised. The tensile test was performed until the adhesive or cohesive fracture was achieved. All the experimental procedures including cleaning and preparing the specimens and application of the adhesives were performed at room temperature and air moisture content of 17 g/m^3. The specimen surfaces were then examined using an FEI Quanta 200 FEG environmental scanning electron microscope (SEM) under high vacuum.

Results and discussion

Effect of surface roughness

The effect of roughness on the single-lap-joints of the adhesively bonded specimens was evaluated by comparing the shear strengths. The results of the shear strengths measured with the A1 adhesive are plotted for the individual alloys at each roughness and displayed in Fig. 2. The graphs displays a similar trend for all the alloys tested, with an initial

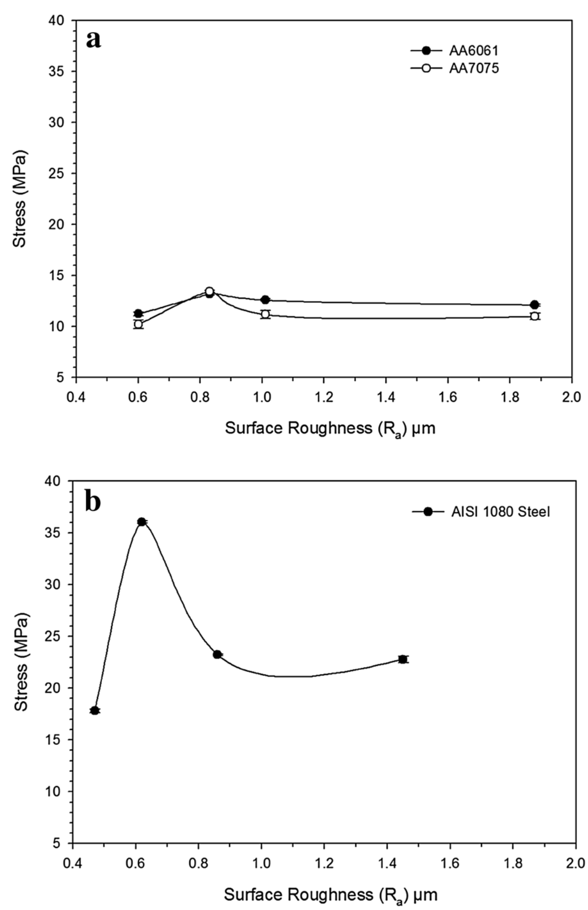

Fig. 2 Plot displaying the surface roughness (R_a) against the shear strength of the single-lap-joints of the **a** aluminum alloys and **b** steel alloy bonded with A1

increase to a peak shear stress as the surface roughness increased and subsequently a sharp and continuous decrease with surface roughness increase. The peak shear strength was observed at a surface roughness (R_a) of 0.83 µm for the aluminum alloys (Fig. 2a) and 0.62 µm for the steel alloy (Fig. 2b). Each of the alloy surface roughness corresponding to the peak stress were achieved from grinding with the 240 grit SiC emery papers. Alloy surfaces ground with the 320 grit SiC emery papers, displaying a surface roughness (R_a) of 0.60 µm for the aluminum alloys (Fig. 2a) and 0.47 µm for the steel alloy (Fig. 2b), were observed to possess the lowest joint shear stresses for each of the alloys. A comparison of the corresponding shear strengths at each roughness for the alloys, displayed little difference in the corresponding shear stresses between the AA6061 and AA7075 alloys (Fig. 2a). However, the shear strengths observed for the steel alloy were much higher than those noted for either of the aluminum alloys.

Figure 3 displays the shear strengths results for the A2 adhesive plotted against the surface roughness (R_a) for each alloy. A similar trend in the graphs was observed for both the aluminum alloys (Fig. 3a), with the fluctuation of shear stress with surface roughness increase. However, the AISI 1080 steel (Fig. 3b) was observed to follow a different trend, with the steady decrease of shear stress with surface roughness till a low point was

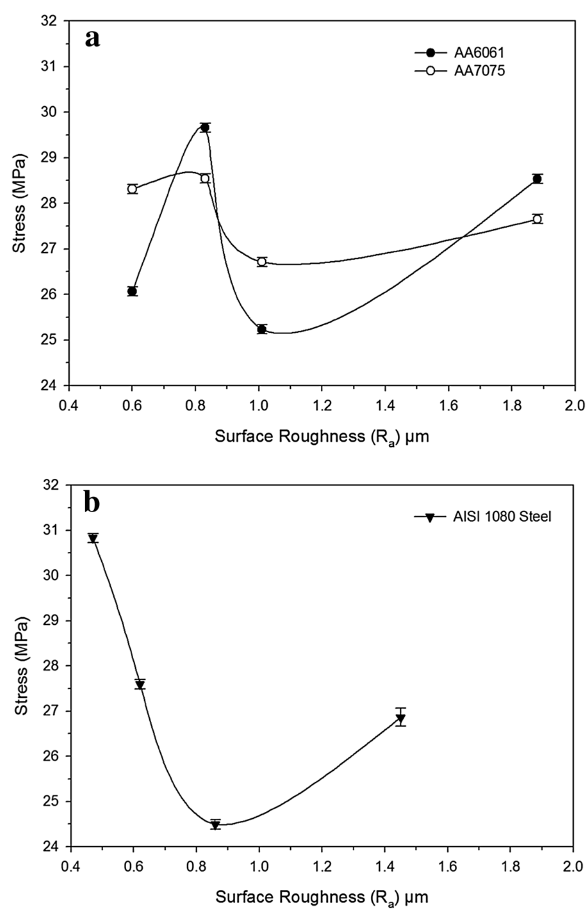

Fig. 3 Plot displaying the surface roughness (R_a) against the shear strength of the single-lap-joints of the **a** aluminum alloys and **b** steel alloy bonded with A2

reached and a subsequent increase in shear stress was perceived. The peak shear stress was observed at surface roughness (R_a) of 0.83 µm for the aluminum alloys (Fig. 3a) and at 0.47 µm for the steel alloy (Fig. 3b). The surface roughness for peak shear stress for the aluminum alloys was achieved from grinding with the 240 grit SiC emery papers while that for the steel alloy was from grinding with the 320 grit SiC emery papers. The lowest shear stresses were observed at surface roughness (R_a) values of 1.01 µm, for the aluminum alloys (Fig. 3a), and 0.86 µm, for the steel alloy (Fig. 3b), which were all achieved from grinding with the 120 grit SiC emery papers. The shear stresses with this adhesive were within similar ranges for all the alloys at the corresponding surface roughness values.

An optimum surface roughness for achieving maximum adhesive strength was observed for all the alloys tested regardless of the adhesive used. A similar observation of optimum surface roughness for maximum bonding strength was observed by Budhe et al. [20], who compared the effect of surface roughness on bonding strength for wood and aluminum AA6061. It can be observed that for the aluminum alloys the maximum adhesive bonding strength was observed at a surface roughness (R_a) of 0.83 µm for both adhesives, which would imply that for this particular alloys, the adhesive type does not have much of an influence on the optimum surface roughness for maximum adhesive shear strength. The maximum adhesive strength of the steel alloy was observed to occur at different surface roughness for the A2 ($R_a = 0.47$ µm) and A1 ($R_a = 0.62$ µm) adhesives, implying that the adhesive type has an influence on adherend surface roughness that yields the maximum bond strength. It is interesting to note that for the A1 adhesive the maximum adhesive strengths were observed at surface roughness values achieved from grinding with the 240 grit SiC emery paper.

An evaluation of the adhesive shear strengths also revealed the effect of the adherend material on the adhesive bond strength. Similar observations have been previously made, with researchers noting that the stiffer, stronger adhrends possessed stronger bond strengths. The A1 displayed higher adhesive bond strengths for steel in comparison to both aluminum alloys, with adhesive shear strengths for the steel alloy being at least twice those of the aluminum alloys. The difference in adhesive shear strengths with adherend material was not as distinct with the A2 adhesive. There was not much disparity observed between the adhesive shear strengths for the steel and aluminum alloys, except for adhesive strenghts observed at surface roughness values obtained with the 320 grit SiC emery papers. Although the maximum adhesive shear strength was observed with the steel alloy, the lowest shear strength was also observed with this alloy. Therefore, the type of adhesive would also influence the extent the adherend material impacts the bond strength.

A comparison of shear strength values for both adhesives revealed higher shear stress using the A2 adhesive with the aluminum alloys at all surface roughness values. The shear strength values of the AISI 1080 steel were within similar ranges with only a slight variation in shear strengths observed at surface roughness (R_a) of 0.47 µm where A2 possessed almost twice the shear stress and 0.62 µm where A1 was distinctly higher. However, the trends for each of the adhesives were distinctly different and while the peak shear stresses were observed at similar surface roughness values for the aluminum alloys, they were observed at different surface roughness values (0.47 µm for A2 and

0.62 μm for A1) for the steel alloy. The lowest shear stresses were observed at different surface roughness values with both adhesives for all the alloys.

In summary, an optimum surface roughness was observed to induce a maximum bond strength, regardless of the adhesive type or alloy. However, while increasing the surface roughness of a material would result in increasing the adhesive strength, this action becomes detrimental after a critical surface roughness, which is dependent on the adherend material. The bond strength was also observed to be dependent on the adherend material and the adhesive type.

Effect of surface oxidation

As the A1 adhesive showed greater disparity with tests assessing the effect of surface roughness, experiments to evaluate the effect of surface oxidation on the adhesive joint shear strengths were performed only with this adhesive. The surfaces of adherends used for these tests were ground to the optimal surface roughness (R_a) which displayed the maximum bond strength for this adhesive, i.e., 0.62 μm for the aluminum alloys and 0.47 μm for the steel alloy. As stated earlier, the alloy specimens were heated prior to the application of the adhesives to temperatures of 100, 200 and 300 °C for 60 mins to

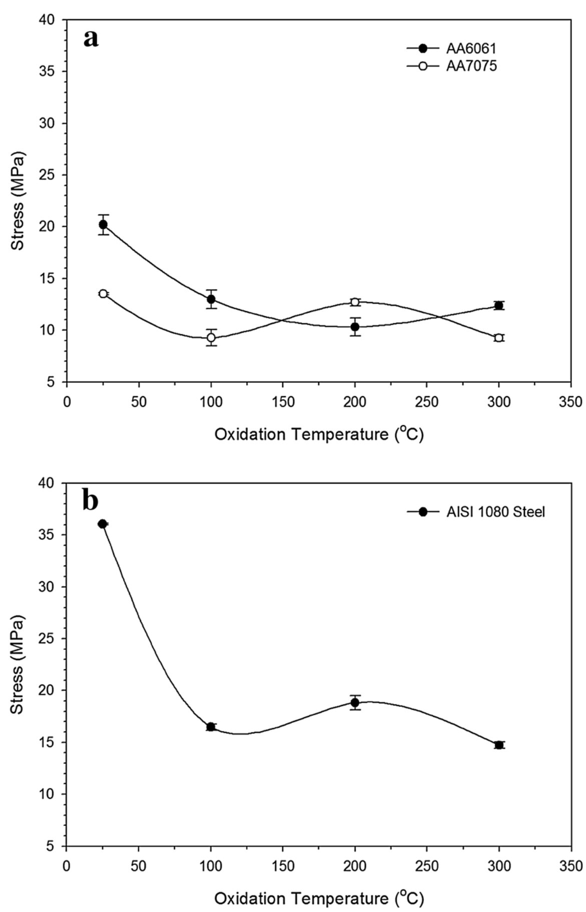

Fig. 4 Plot displaying the shear stress of the single-lap-joint against the heat treatment temperature for the **a** aluminum alloys and **b** steel alloy bonded with the A1 adhesive

develop an oxide layer on each of the specimens. The results of the shear strengths measured at these temperatures were compared with the shear strengths measured at room temperature and plotted for each alloy as displayed in Fig. 4. The peak shear stresses for each of the alloys were observed at room temperature, the oxide layers developed from heating the alloys were observed to reduce the adhesive shear stresses for all the alloys. The lowest shear stresses were observed at 200 °C for the AA6061 alloy (Fig. 4a) and 300 °C for the AISI 1080 steel (Fig. 4b). While the lowest shear stress for the AA7075 (Fig. 4a) was observed at 300 °C, the difference between the shear stresses at 100 and 300 °C was minute and therefore could be considered similar.

The trend for the graphs of the AISI 1080 steel (Fig. 4b) and the AA7075 aluminum alloy (Fig. 4a) were rather similar, displaying a fluctuation of the shear stresses with heat treatment temperature increase after an initial decrease from 25 °C. The trend for the AA6061 alloy (Fig. 4a) though displays a continuous drop from 25 to 200 °C after which a slight increase is observed at 300 °C. Again the steel sample displayed the highest shear stresses at each temperature while the AA7075 alloy displayed the lowest shear stress at each temperature except at 200 °C where the AA6061 alloy displayed the lowest shear stress.

These results display the influence of the adherend surface condition on the bond strength between the metal and the adhesive. The results above indicate that as the heat treatment temperature rises, the increase in the oxide content on the surface of the specimen will result in the reduction of the adhesive shear strength. It can be seen that the shear strength of the joint was maximum at room temperature, were the oxide content of the alloy surfaces would ideally be at a minimum and would have good adherence to the aluminum alloy surface. However, as can be seen in Fig. 4, shear strength of the specimens slightly increases when the heat treatment temperature changes from 100 to 200 °C. Therefore, it can be suggested that the adhesives are not resistant to the environmental effects to the adherend surfaces. The impact that oxidation of the adherend surface has on adhesive strength was dependent on the alloy type, as a higher percentage reduction in shear stress between 25 and 100 °C was observed for steel (54%), while for the aluminum alloys it was an average of 34%.

It has been proposed that the oxides formed on the adherend surface might inhibit the chemical bond between the adhesive and the adherend surfaces [3]. Energy dispersive spectrometry (EDS) was therefore performed on the adherend surfaces to investigate the effect of the surface oxides on the adhesive junction strength. The EDS maps of the AA6061 surfaces heated treated at temperatures of 100, 200 and 300 °C are displayed in Fig. 5, while the similar surfaces for AA7075 are displayed in Fig. 6 and Fig. 7 displays the surfaces for the AISI 1080 steel. The EDS maps display the distribution of aluminum, magnesium and oxygen for the aluminum alloy surfaces while for the steel surface, it displays the iron and oxygen distribution.

The surfaces of all the heat treated aluminum alloys (Figs. 5, 6) were observed to be covered with magnesium and oxygen. The magnesium distribution on the heat treated surfaces were predominantly coincident with the oxygen distribution indicating that the oxygen on the alloy surfaces was due to the formation of a magnesium-rich oxide, likely MgO, on heating. The aluminum alloy surfaces, AA6061 (Fig. 5a) and AA7075 (Fig. 6a) without heat treatment possessed a lower concentration of magnesium and oxygen on

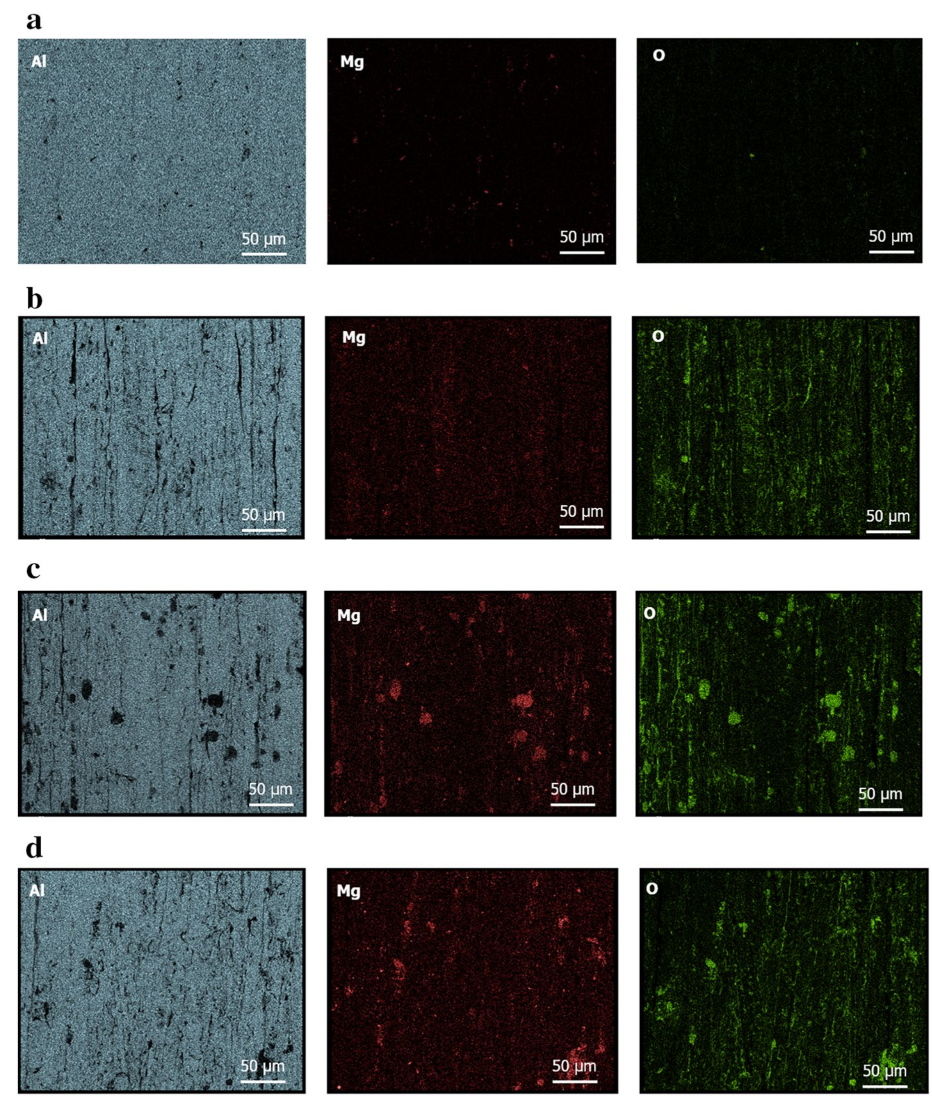

Fig. 5 EDS maps displaying the element distribution on the AA6061 aluminum alloy surface heat treated at **a** 25 °C, **b** 100 °C, **c** 200 °C and **d** 300 °C

their surfaces. The magnesium under this condition was not observed to be coincident with oxygen, indicating that the oxide was most likely Al_2O_3, which has good adhesion to the aluminum subsurface and is known to acts as a protective layer [22]. The oxides on the heat treated AA7075 alloy (Fig. 6b–d) were observed to predominantly occur within the grooves created during the grinding of the alloy surfaces, while for the AA6061 alloy (Fig. 5b–d) they covered the surface at 100 °C but at higher temperatures they occurred within grooves and as MgO islands. It should be noted that while magnesium diffusion in aluminum alloys is enhanced by surface defects and voids in the alloy and oxide layer, the disparity of concentration of magnesium at the surface is also associated to the roughness of the sample, which in this case was induced by grinding [24]. The local enrichment of MgO oxide at the metal/adhesive interface thus reduced the stability of the adhesive joints [21].

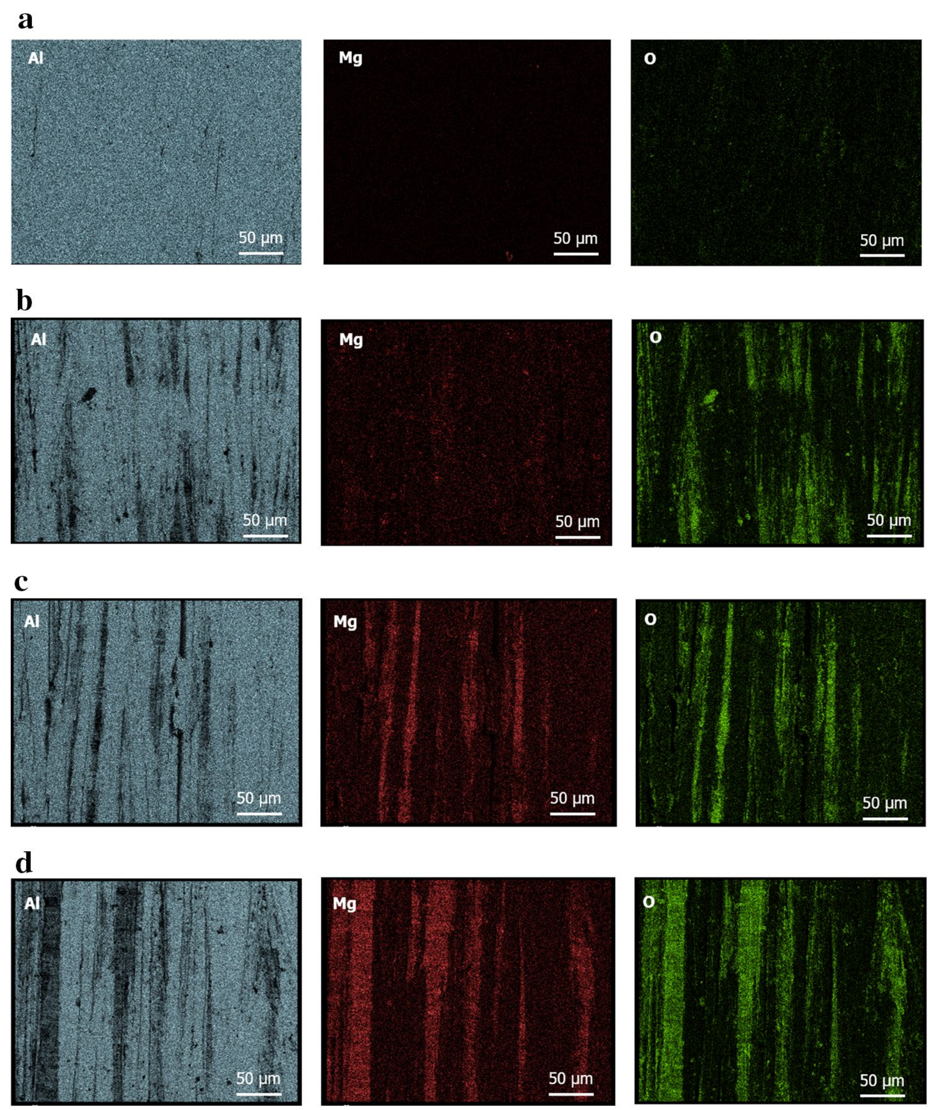

Fig. 6 EDS maps displaying the element distribution on the AA7075 aluminum alloy surface heat treated at **a** 25 °C, **b** 100 °C, **c** 200 °C and **d** 300 °C

Magnesium-rich oxides have been reported to lead to problems with adhesion of organic films and adhesives, while their accumulation on aluminum alloy surfaces are believed to be detrimental to the durability of the adhesive bonds [22, 23]. The reduction in adherend strength when the aluminum surfaces are heat treated prior to the application of the adhesive would be due to the occurrence of these oxides on the aluminum alloy surfaces. A comparison of the concentration of the oxygen on the aluminum surfaces displayed in Fig. 8a revealed that the AA7075 possessed a higher concentration of oxygen on its surface at 100 and 300 °C. At 200 °C, there was little difference in the oxygen concentration on both aluminum alloy surfaces. This analysis is supported by the higher bulk concentration of magnesium in AA7075 (2.1–2.9 wt %) than AA6061 (0.8–1.2 wt %), research has shown that more MgO is observed on aluminum alloys with

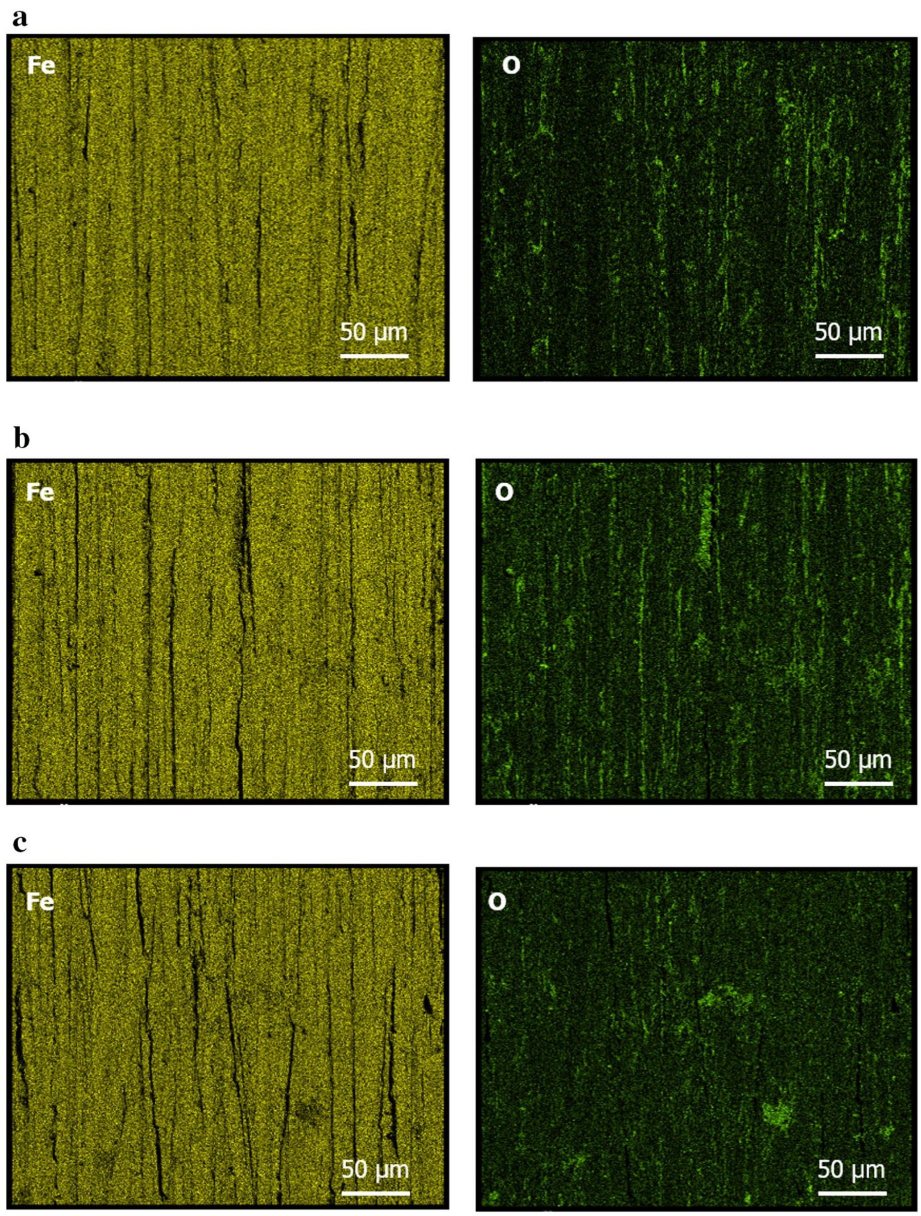

Fig. 7 EDS maps displaying the element distribution on the AISI 1080 steel surface heat treated at **a** 100 °C, **b** 200 °C and **c** 300 °C

high bulk magnesium concentration [25]. The higher MgO concentration on the surface of the AA7075 alloy in comparison to the AA6061 alloy after heat treatment could thus be related to the difference in adhesion strength between both alloys. It should be noted that the oxide film thickness and morphology on aluminum alloys have been noted to be relevant for adhesive bonding and these factors are strongly related to the heat treatment and magnesium concentration of the aluminum alloys [22]. These tests indicate that low bulk concentrations of magnesium might be strongly related to higher adhesive shear stresses for aluminum alloys.

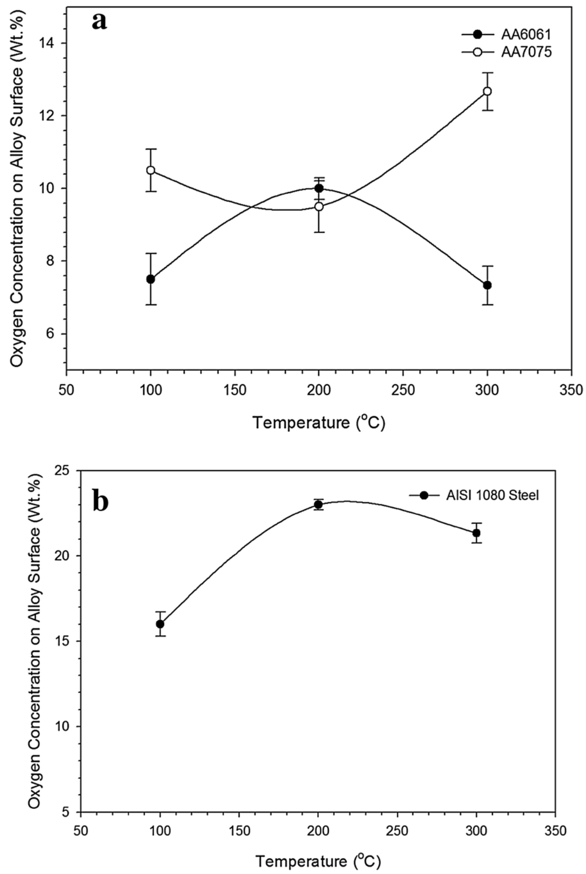

Fig. 8 Plot displaying the oxygen concentration on the surfaces of heat treated **a** aluminum alloys and **b** steel alloy at various temperatures

The increase in the oxygen concentration on the AISI 1080 steel surfaces (Fig. 8b) was also coincident with the reduction of the adhesion shear stress. The oxides, most likely Fe_3O_4 and Fe_2O_3, their thickness and composition are dependent on the temperature and composition of the steel alloy [26]. Fe_3O_4 is reported as the dominant oxide at 200 °C, and has been observed to have good oxide adherence with the steel substrate [27, 28]. At 300 °C, a change in the oxidation rate and the dominant oxide begins [28, 29]. The formation of Fe_2O_3 with increasing temperatures, from 300 °C, has been reported to be accompanied by oxide separation from the metal surface [28, 29]. These oxides were observed to occur predominately within the grinding grooves of the steel. Although the oxygen concentration on the steel surfaces was much higher than that of both aluminum alloys (Fig. 8), the adhesive strength of the steel was still higher than both aluminum alloys regardless of the heat treatment (Fig. 4). The fluctuation of the adhesive strength with the increase of the heat treatment temperature for both the aluminum and steel alloy surfaces could be a result of either or a combination of the difference in oxide induced roughness, oxide thickness and composition and the oxide adhesion to the alloy surface on these alloys at each of the heat treatment temperatures.

The oxides on the metal surfaces, like the porous MgO on aluminum surfaces and the descaling Fe_2O_3 do not provide a strong bond between the alloy and adhesive [21]. An

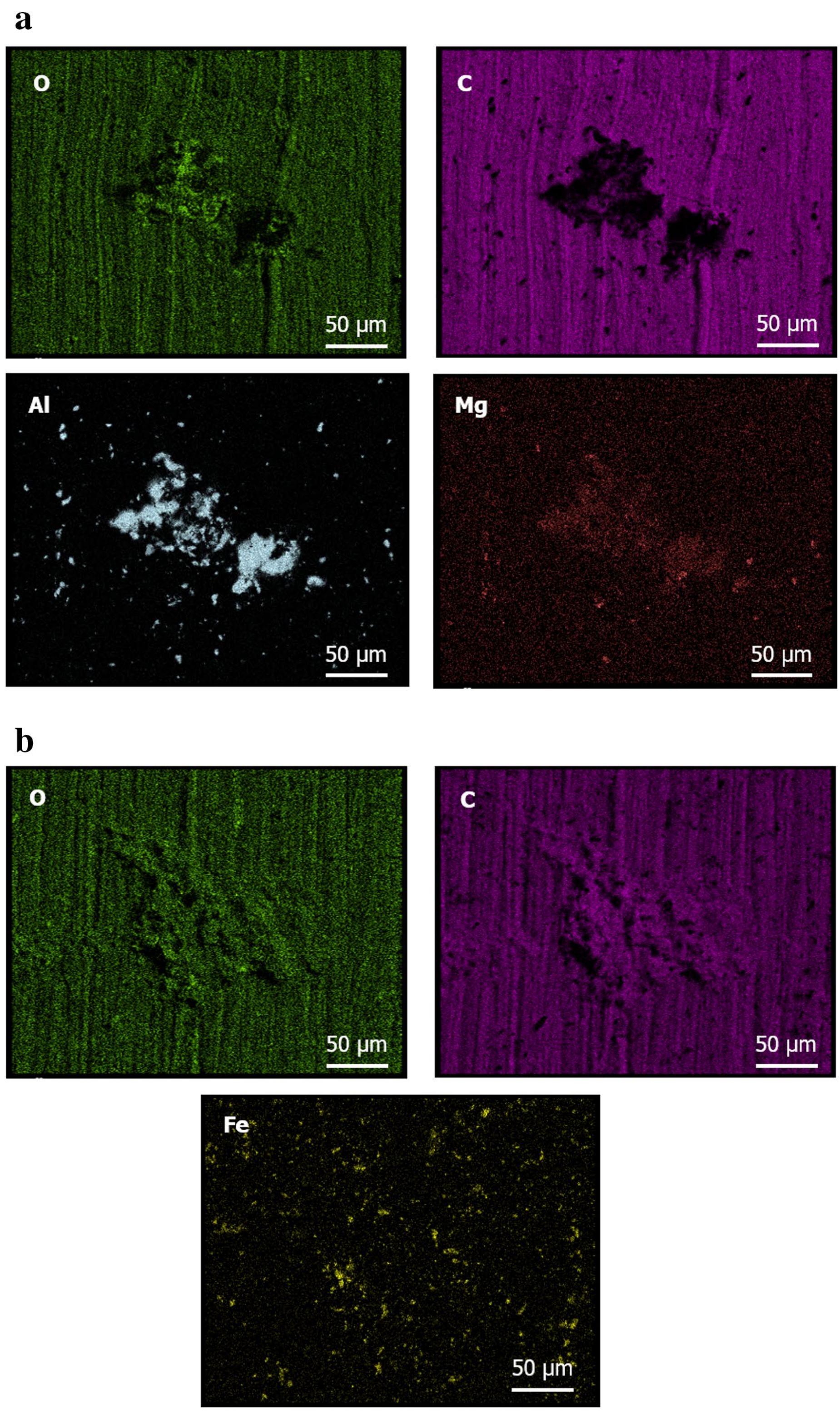

Fig. 9 EDS maps displaying the element distribution of debris caught on the A1 adhesive from **a** AA6061 aluminum alloy at 300 °C and **b** AISI 1080 steel at 200 °C

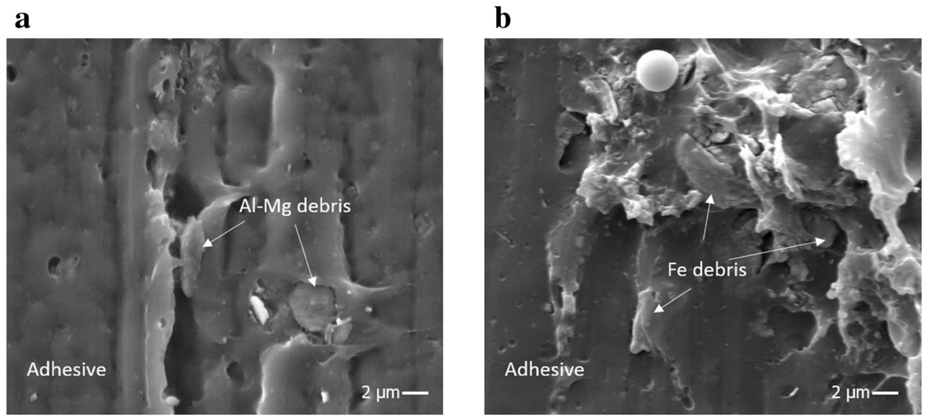

Fig. 10 SEM images of debris caught on the A1 adhesive from the **a** AA6061 aluminum alloy at 300 °C and **b** AISI 1080 steel at 200 °C

Table 3 Values of constants in equation for the A1 adhesive

Alloy	a	b	c	d
AA6061	−0.4417	2.705	−4.5433	14.4
AA7075	−1.255	8056	−16.705	20.4
AISI 1080 steel	−7.2383	49.62	−97.752	78.15

examination of the adhesive on the heat treated samples after the tests revealed oxide particles embedded within the adhesive. Oxide debris rich in magnesium, aluminum (Fig. 9a) and iron (Fig. 9b) were observed covering the surface area of the adhesive on the aluminum alloy and steel respectively. High magnification SEM images of the adhesive on the aluminum (Fig. 10a) and steel (Fig. 10b) alloys confirmed these particles were embedded within, beneath and lying on the surface of the adhesive. The adhesive joint formed with metal alloys covered with decohesive oxides loses adhesive strength as a result of these loosely adhered oxides compromising the adhesive bond. Therefore, oxide adherence to the adherend surface would be a critical factor that would greatly influence the adhesive shear strength.

Linear regression analysis

Regression analysis was performed on the experimental data for each of the alloy adherend joints in relation to the surface roughness (R_a). Each of the equations obtained to model the shear strength of the single-lap-joints bonded with the mentioned adhesives were in the form of Eq. (1) below.

$$\tau_s = aR_a^3 + bR_a^2 + cR_a + d \tag{1}$$

where, τ_s is the shear stress in MPa. R_a is the surface roughness in µm and a, b, c and d are constants.

The values of a, b, c and d for each of the adherend alloys bonded with A1 are displayed in Table 3 and with A2 are displayed in Table 4. The equation can be used to calculate the approximate shear stress for the surface roughness (R_a) values between 0.60 to

Table 4 Values of constants in equation for the A2 adhesive

Alloy	a	b	c	d
AA6061	−2.6267	19.625	−43.788	55.32
AA7075	−8.805	6.215	−13.95	36.19
AISI 1080 steel	−0.8883	8.065	−20.347	40.03

1.88 μm and 0.47 to 1.45 μm for aluminum and steel alloys tested respectively. However, this equation is valid specifically for the adherend-adhesive combinations of AA6061, AA7075 and AISI 1080 steel with A1 and A2 adhesives only.

Conclusions

The effect of the surface conditions, i.e., roughness and oxidation, of AISI 1080 steel, AA6061 and AA7075 aluminum alloys on the adhesive bond strength was tested with single-lap-joints using two different epoxy adhesives. The following conclusions were derived:

1. The optimum surface roughness value which has been surmised to provide a maximum adhesive bond strength is dependent on the adherend material and the type of adhesive employed.
2. The shear strength of the adhesive joint is influenced by the concentration and distribution of oxides covering the adherend surface due to heat treatments. In the case of aluminum alloys, the distribution and concentration of oxides on the alloy surface is determined by the heat treatment temperature and the bulk magnesium concentration of the alloy.
3. The nature of the oxides formed on the adherend material surface and its adhesiveness to the adherend material significantly influence the shear strength of the adhesive joint. In the case of aluminum and steel alloys, the formation of a porous MgO, and descaling Fe_2O_3 oxides respectively, reduced the adhesive bond strength.

Authors' contributions

MHK and OAG were responsible for completing the article. MHK, ARR, and AE performed the experimental work from the preparation of the samples to the testing of the specimens. OAG carried out further surface analysis of the sample. ARR and AE were involved in the discussion and significantly contributed to making the final draft. All authors read and approved the final manuscript.

Competing interests

The authors declare that they have no competing interests.

Received: 26 October 2016 Accepted: 29 November 2016
Published online: 12 December 2016

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