THE EFFECTS OF BONDING TEMPERATURE AND SURFACE ROUGHNESS ON THE SHEAR STRENGTH OF BONDED ALUMINIUM LAMINATES USING POLYPROPYLENE BASED ADHESIVE

L.F. Ng[1], D. Sivakumar[1], X.J. Woo[2], S. Kathiravan[1] and I. Siva[3]

[1]Faculty of Mechanical Engineering,
Universiti Teknikal Malaysia Melaka, Hang Tuah Jaya, 76100 Durian
Tunggal, Melaka, Malaysia.

[2]Faculty of Electrical Engineering,
Universiti Teknikal Malaysia Melaka, Hang Tuah Jaya, 76100 Durian
Tunggal, Melaka, Malaysia.

[3]Centre for Composite Materials, Department of Mechanical Engineering,
Kalasalingam University, 626126, India.

Corresponding Author's Email: [1]nglinfeng@yahoo.com

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ABSTRACT: The high strength to weight ratio behaviour of aluminium alloys is particularly attractive in the transportation field to reduce the energy consumption. In this study, the effects of bonding temperature and the surface roughness on the single lap shear of bonded aluminium 5052 were studied. The bonding temperatures were in the range of 140°C to 170°C at an interval of 15°C whereas the surface roughness values were at 0.24, 0.49, 0.60 and 0.98. The bonded aluminium sheets were fabricated through the hot compression method in which the adhesives were located between the aluminium sheets. Single lap shear test was conducted at room temperature with reference to ASTM D1002. The results demonstrated that the bonding temperature and surface roughness of aluminium sheets influenced the lap shear strength. The aluminium with surface roughness value of 0.98 evidenced the highest shear strength regardless of bonding temperatures. When comparing the shear strength of aluminium laminates with different bonding temperature, aluminium with 170°C attested a slightly higher shear strength compared to 155°C and 140°C. The shear strength of aluminium with bonding temperature of 170°C was 0.71% and 9.81% higher than 155°C and 140°C respectively at surface roughness value of 0.98.

KEYWORDS: *Metal Laminates; Shear Strength; Aluminium; Surface Roughness; Bonding Temperature*

1.0 INTRODUCTION

Recently, aluminium alloys have been broadly employed in a wide variety of applications especially where the high strength to weight ratio characteristic of the material is critical [1-4]. It is well known that aluminium alloys possess the high strength to weight ratio behaviour compared to other metallic alloys such as steel. Despite the advantages offered by aluminium alloys, they are also susceptible to the rapid fatigue crack growth rate, which results in the fracture of the structural components. At present, high fatigue crack resistance characteristic of the materials is demanded in transportation fields such as aerospace and automotive industries [5]. However, it was found in Fokker Aero-structures of Netherlands that the adhesively bonded laminated structures could avoid the rapid fatigue crack propagation in comparison to a single sheet of metallic alloys [6]. The adhesives in the laminated structures act as a crack retarder which hinders the rapid fatigue crack propagation from one layer of the metallic alloys to another, resulting in improved fatigue crack resistance. The crack growth rate persists until the crack initiates at the neighbouring sheet as well. The performance of the adhesive is particularly important in determining the mechanical response of the current materials used in aerospace industries, namely, Fibre Metal Laminates (FMLs). FMLs are considered an advanced hybrid material which consists of metallic alloys together with composite materials [7]. The poor adhesive performance results in the delamination of the metallic layers and composite in FMLs, leading to the weak mechanical response of such materials. Thus, an excellent adhesive level in FMLs is particularly critical in order to ensure optimum mechanical strength.

Materials can be assembled through either mechanical or adhesively joining methods. A proper joint design is required to prevent overweight and structure defections irrespective of joining methods [8]. There are numerous studies that have been conducted on the bolted joint behaviour under different geometrical parameters [9–11]. They have revealed the excellent potential of using the bolted joint to assemble different materials. However, adhesive joining method is still considered as the most frequent technique applied for the manufacturing process as this method offer numerous advantages such as weight reduction, less stress concentration location and corrosion resistance [12]. Apart from that, the adhesive joining method also gives benefits of improved stiffness, energy absorption and less vibration [13]. In fact, adhesive joining methods have been extensively used in aerospace industry for joining of structural components since the past few decades due to their lightweight and low cost behaviour [14]. There have been several studies regarding the effects of adhesives, type of adherent and bond line thickness on the shear strength of the materials [15–17]. Although adhesive joining methods are considered advantageous in joining thin metals and composites in comparison to welding and mechanical fastening, the structural performance is governed by the debonding and fracture. Several factors determine the characteristics of the adhesives, which include atomic arrangement, chemical properties and diffusivity of the constituent elements [18]. Therefore a good adhesion between the two materials depends on the adhered surface condition. Surface pre-treatment involves contaminant elimination, chemically activating and providing a bonding site for the adhered surfaces and initiation resistance of hydration and environmental attack [19]. To achieve the optimum bonding level, a proper adhesive joint design is required to improve its efficiency and to reduce its limitations. The bonding temperature and the surface treatment of the adherend need to be considered during the joining process to ensure the durability of the bonding. One of the most common adherend surface treatments is the surface finish as this has a decisive effect on the joint properties. It was found that the maximum bonding capability is largely dependent on the surface roughness and the level of surface roughness is governed by the adherend materials [20]. Besides that, the temperature is also considered as one of the important factors that influence the bonding performance of the adhesive due to the polymeric nature of the adhesives [21].

The single lap joint is the most commonly used joining techniques that have been widely applied over the year, and it is the subject of interest among researchers. Furthermore, a typical test used to investigate the adhesive performance is through the single lap joint test. Numerous researchers have done an experimental investigation on the effect of temperature and surface roughness on the single lap joint of bonded metallic layers. Boutar et al. [12] studied the effect of surface roughness on the single lap shear properties of bonded aluminium using polyurethane adhesive. Different grades of grit paper were used, p50, p180 and p1000. The single lap shear properties of treated aluminium with different grades were compared to those of untreated aluminium. The findings demonstrated that the shear strength increased from the non-abraded aluminium surface to that aluminium polished with p1000 abrasive paper. The shear strength started to drop once the grade of the abrasive paper exceeds p1000. This could be due to the adhesive did not spread well on the surface, causing gas molecules trapped in the asperity valleys which in turn reduces the bonding capacity. Hussain et al. [22] investigated the interfacial shear behaviour of adhesively bonded aluminium with composite materials. The polypropylene based adhesive was used and the aluminium sheets were subjected to a chemical etching to increase the surface roughness. They noticed the processing temperature for the adhesive bonding was between 140°C to 155°C and the surface treatment did not contribute any significant effect on the shear strength. Putman and Vaidya [23] conducted a similar experimental work on the interfacial shear strength of metal-composite materials using polyurethane adhesive. They revealed that the friction coefficient of the materials contributes up to 83.5% to the shear strength. Saleema et al. [24] conducted an experimental investigation on the effect of surface roughness on the single lap shear strength of aluminium sheets using epoxy adhesives. The aluminium sheets were chemically etched for different periods of time, which were 0, 5, 30 and 60 minutes. A noticeable enhancement in the shear strength was observed when the aluminium sheets were subjected to chemical etch as this treatment improves the surface roughness. Budhe et al. [25] explored the effect of surface roughness on the shear strength of different adherend materials. The aluminium sheets were bonded to the wood using epoxy adhesives. They concluded that the increase of surface roughness on the aluminium sheets improved the bonding strength of the materials. Nevertheless, the increase of surface roughness of the wood reduced the adhesive bond strength. Borsellino et al. [26] evaluated the effects of resin and surface treatment on the single lap shear properties of aluminium. Different types of adhesive agents were used, which include orthophtalic polyester, vinyl ester and epoxy to bond the aluminium sheets. From the findings, it was shown that the epoxy adhesives demonstrated the highest joint resistance whereas vinyl ester adhesives gave the highest wettability. The surface treatment on the substrate materials had been identified that can improve the shear strength until an optimal topography of the surface is reached. Zielecki et al. [27] investigated the surface topography influences on the single lap shear strength of steel using epoxy adhesive at the interface after mechanical surface treatment using grit blasting. They revealed improvement in the lap shear strength as a result of subsequent grit blasting.

The aforementioned studies focus more on the lap shear behaviour using epoxy based adhesives. It is clearly noticed that there are still very limited studies that explore the lap shear behaviour of polypropylene based adhesives with aluminium adherend surfaces. Therefore, this study intends to investigate the effect of surface roughness of the aluminium surface and adhesive bonding temperature on the shear strength of adhesively bonded aluminium laminates.

2.0 METHODOLOGY

Aluminium 5052-H32 sheets with a thickness of 2 mm were supplied by Novelis Inc., United States. Polypropylene (PP) based adhesives with a density of 0.91 g/cm^3 were provided by Collano Adhesives AG, Switzerland. The aluminium sheets were abraded using silicon carbide abrasive paper with 150, 120 and 80-grit size to increase the surface roughness. The bonding area was then degreased using ethanol to remove the surface impurities. The aluminium sheets were adhesively bonded through the incorporation of PP adhesives at the interface. Three bonding temperatures of 140°C, 155°C and 170°C were fixed during the heat compression process to study the temperature effect on the bonding strength. A pressure of 1 MPa which is commonly used in the FML fabrication was applied on the aluminium during the heat compression process. 170°C which is the softening temperature of thermoplastic composites was fixed as the upper limit temperature since PP adhesive has been widely used to bond the aluminium skin layers to the thermoplastic-based composite materials. The single lap shear test was conducted according to ASTM D1002 at room temperature and cross-head displacement rate of 2 mm/min using Instron 5969 Universal Testing Machine. The specimens were carefully tightened during the single lap shear test to avoid the occurrence of bending moment. The specimen during the lap shear test is depicted in Figure 1. The test was conducted until the adhesive fracture. Table 1 summarises the chemical compositions of aluminium 5052-H32. The geometrical dimension of the single lap joint specimen is shown in Figure 2.

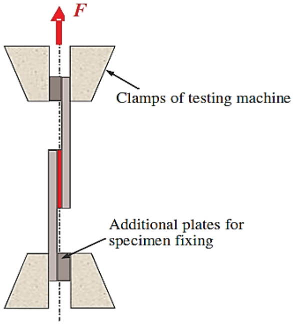

Figure 1: Specimen during the lap shear test [28]

Table 1: Chemical compositions of aluminium 5052 H-32 [29]

Material	Si	Fe	Mg	Ti	Mn	Zn	Cu	Cr	Al
Al 5052 (%)	0.25	0.4	2.8	0.15	0.1	0.1	0.1	0.25	95.85

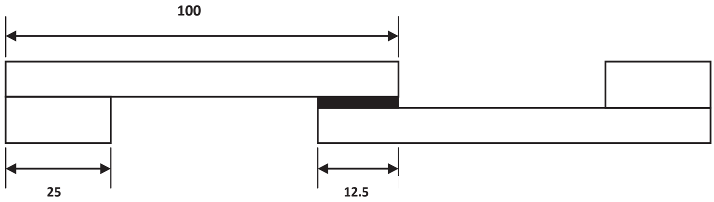

Figure 2: Geometrical dimension of the single lap joint (unit: mm)

3.0 RESULTS AND DISCUSSION

The lap joint tests had been conducted on the specimens to determine the lap shear behaviour of adhesively bonded aluminium sheets. The bonding level of the adhesively jointed aluminium sheets is highly dependent on the adhesive layer. The shear strength of the lap joint can be determined in accordance with the recorded maximum tensile stress for each joint. The lap shear strength is determined using the Equation (1) [21].

$$\tau = \frac{F_{max}}{\mathrm{W} \times \mathrm{L}} \tag{1}$$

where τ is the shear strength of the lap joint, F_{max} is the maximum tensile load from the lap shear test, W is the joint width and L is the joint overlap length.

The surface treatment acts as an important parameter that affects the shear strength of the materials. The surface roughness (R_a) values of the aluminium surfaces were obtained from four different points and the average values were summarised as shown in Table 2. The standard deviation is included in the parentheses as well. Figure 3 and Figure 4 demonstrate the surface texture of aluminium with different R_a values. The surface roughness of aluminium increased with the increase of the grit size of abrasive paper. As can be noticed in Figure 3 and Figure 4, the surface roughness of the abraded aluminium increased as compared to the non-abraded aluminium. Furthermore, the increase of the grit size of the abrasive paper increased the surface roughness values of the aluminium, which could be evidenced in Table 2.

Table 2: Average surface roughness (R_a) values of aluminium surfaces

Surface treatment	R_a (μm)
Non-abraded	0.24 (0.03)
150 grit	0.49 (0.07)
120 grit	0.60 (0.07)
80 grit	0.98 (0.03)

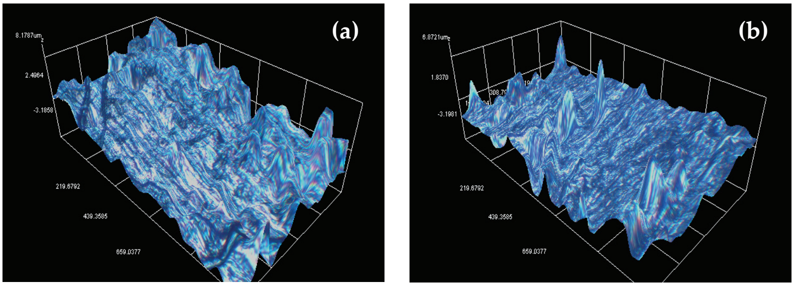

Figure 3: 3D view of surface texture: (a) Non-abraded (b) 80-gritsize

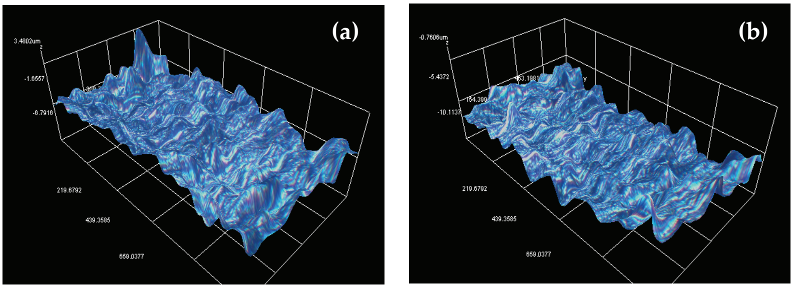

Figure 4: 3D view of surface texture: (a) 120-gritsize (b) 150-gritsize

In all cases, the load-displacement curves increase linearly until adhesive failure occurs. Moreover, abraded aluminium laminates with R_a value of 0.98 have demonstrated the highest maximum load irrespective of different bonding temperatures. Figure 5 shows the load-displacement curves of single lap shear of bonded aluminium laminates at a bonding temperature of 140°C. The load of single lap shear of non-abraded aluminium laminates was compared to abraded laminates with different R_a values. From Figure 5, it is noticeable that the maximum load of single lap shear of abraded aluminium laminates was significantly higher than non-abraded aluminium laminates. The non-abraded aluminium laminates with R_a value of 0.24 demonstrated the lowest load when compared to other abraded aluminium laminates. The maximum load of abraded aluminium laminates with R_a value of 0.98 was 76.9% higher than those of non-abraded aluminium laminates with R_a value of 0.24.

Figure 6 and Figure 7 show the load-displacement curves of single lap shear of bonded aluminium laminates at a bonding temperature of 155°C and 170°C respectively. From Figure 6 and Figure 7, the similar trend as in Figure 5 was observed where the increase of surface roughness increases the maximum load of the aluminium laminates. It was noticed that the maximum load of abraded aluminium laminates with R_a value of 0.98 was 60.0% and 49.4% higher than those of non-abraded aluminium with R_a value of 0.24 at bonding temperature of 155°C and 170°C, respectively.

In fact, the mechanical surface treatment provides a rough surface to the materials, which eventually improves the mechanical interlocking of the adherend materials by forming mini scarf joints as depicted in Figure 3 and Figure 4. The mini scarf joints increased the interfacial area of adhesive and the aluminium alloys and thus improving the shear strength. Meanwhile, the rough surface also increases the wettability of the adherend, which indicates that the adhesives can be bonded to the metallic layers very well, resulting in enhanced maximum load.

In fact, the increase in the wettability implies that the polypropylene adhesive can be distributed well at the interface of the adherends, which has a significant effect on improving the bonding strength. In contrast, the lack of surface roughness in those of non-abraded aluminium alloys could not provide either the mechanical interlocking or wettability to the adhesive and adherend. Therefore, the non-abraded aluminium alloys exhibited lower shear strength compared to those of abraded aluminium laminates. Similar findings were also found by Sahid and Hashim [30] and Uehara and Sakurai [31] in which they reported an increase in surface roughness of the adherends which were mild steel and brass respectively using epoxy adhesive results in the increase in the mechanical interlocking between the mini scarf joints of the materials, which in turn improves the bonding strength at the abraded surface.

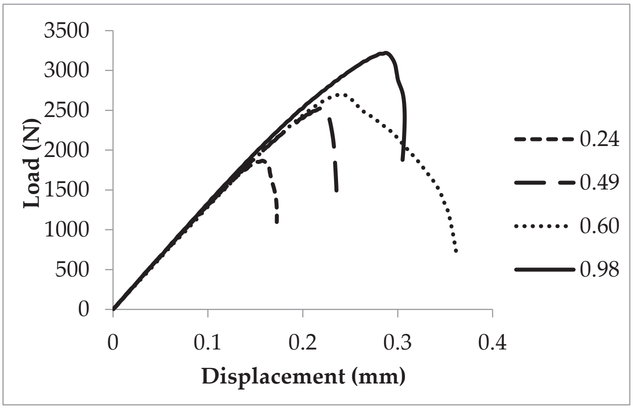

Figure 5: Load-displacement curve of single lap shear of bonded aluminium laminates at a temperature of 140^{0}C

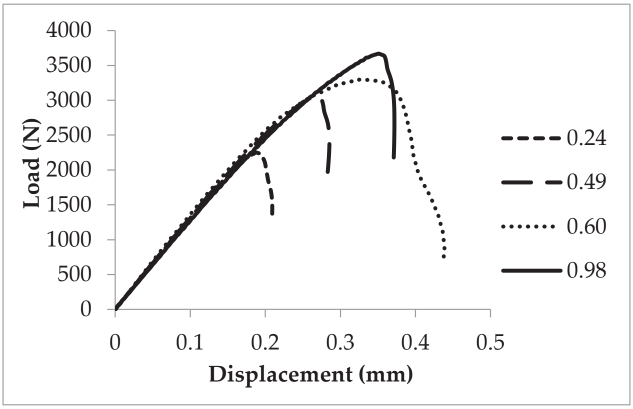

Figure 6: Load-displacement curve of single lap shear of bonded aluminium laminates at a temperature of 155^{0}C

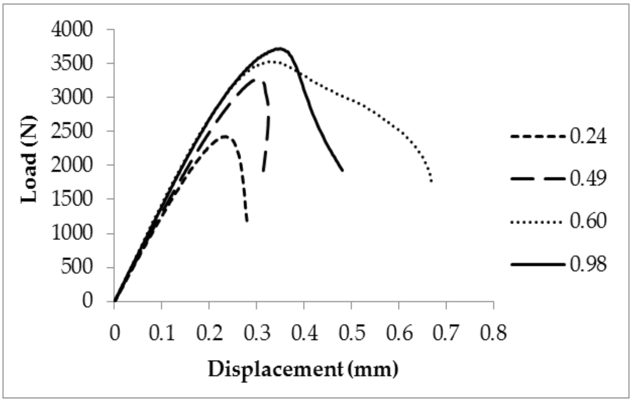

Figure 7: Load-displacement curve of single lap shear of bonded aluminium laminates at a temperature of 170^{0}C

The shear test was repeated three times for the aluminium under different bonding temperatures and R_a values. The data distribution of the maximum shear load was represented in boxplots. Figure 8, Figure 9 and Figure 10 demonstrate the boxplots of the maximum load at different bonding temperatures and R_a values. The upper and lower edges in the boxplots indicate the maximum and minimum values of the load whereas the middle line refers to the median of the maximum shear load. In overall, the values of the boxplots are close to each other although there are some deviations in the test values. This could be due to the limited specimen inconsistency and geometrical inequalities. The variation in the adhesive properties led to the considerably inconsistency of the test values. Due to the variation in the findings obtained, the nominal values were determined to ensure the reliability of the results. Figure 11 depicts the shear strength of bonded aluminium with different bonding temperatures. It is clearly shown that the shear strength of aluminium with bonding temperature of 170 °C was apparently higher than 140°C and 155°C. At R_a value of 0.98, the shear strength of bonded aluminium laminates with a bonding temperature of 170°C was 9.81% and 0.71% higher than the bonding temperature of 140°C and 155°C respectively. This could be attributed to the higher crystallinity of the PP adhesive and thus improving the bonding strength. It has been evidenced that the increase of crystallinity of the polymer could improve the stiffness as well as strength [32]. Furthermore, it was demonstrated that the increase in temperature increases the crystallinity of the PP [33]. At low temperature, the degree of freedom of the polymer chain is high, resulting in lower strength.

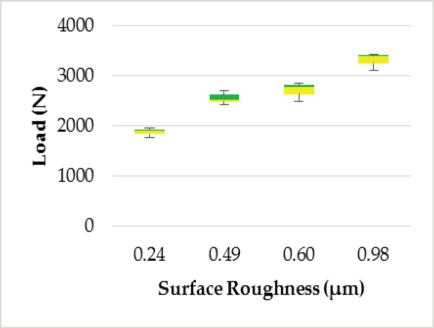

Figure 8: Boxplots of the maximum load at bonding temperature of 140 ^{0}C

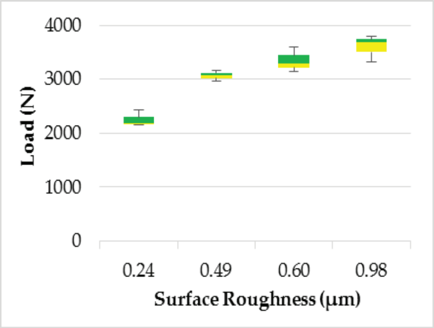

Figure 9: Boxplots of the maximum load at bonding temperature of 155 ^{0}C

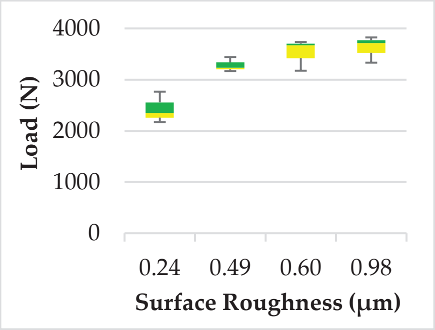

Figure 10: Boxplots of the maximum load at bonding temperature of 170 ⁰C

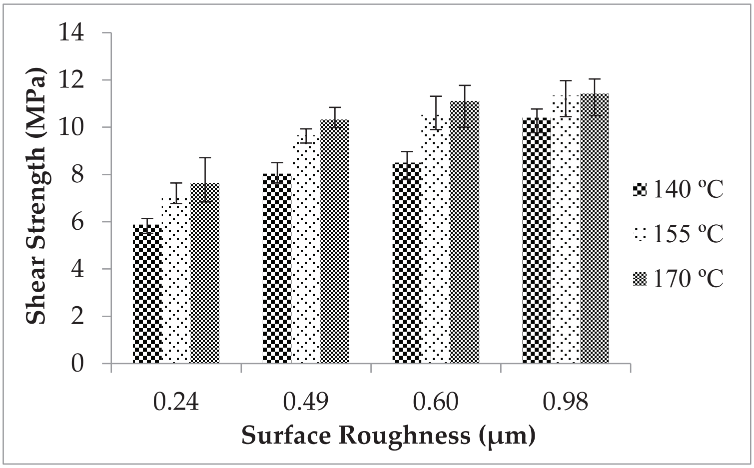

Figure 11: Comparison of shear strength of bonded aluminium with different bonding temperature

4.0 CONCLUSION

This study explores the effect of bonding temperature and surface roughness on the single lap shear behaviour of bonded aluminium laminates. The findings are especially important in the aerospace and automotive industries for bonding purpose. Based on the findings and results obtained, several conclusions can be drawn:

i. Bonded aluminium laminates with mechanical surface treatment provide higher lap shear strength compared to non-abraded aluminium laminates. The mechanical surface treatment increased the R_a value of the aluminium laminates, thereby improves the lap shear strength. The surface treatment with 80-grit size silicon carbide abrasive paper that resulted in the highest R_a value provided the highest lap shear strength compared to 120 and 150-grit size. These findings indicate that the increase of R_a value of the aluminium leads to the increase of the lap shear strength. The improvement was approximately 76.87%, 59.94% and 49.48% for bonding temperature of 140°C, 155°C and 170 °C respectively when the R_a value was increased from 0.24 to 0.98. This is due to the increase in interfacial bonding region, mechanical interlocking and micro-column on the adherend surface.

ii. Bonding temperature indeed influences the lap shear properties of bonded aluminium laminates. From the results obtained, the bonding temperature of 170°C leads to the higher lap shear strength compared to the 140°C and 155°C. The aluminium laminates with R_a value of 0.98 showed 9.81% and 0.71% improvement when the bonding temperature was elevated from 140°C and 155°C to 170°C. The effect of bonding temperature in this study has a major contribution, especially on the thermoplastic adhesive agent.

iii. FMLs fabrication to obtain the optimum mechanical performance in FMLs. Therefore, it was noticed that the bonding temperature of 170°C and the increase of R_a value offered the optimum lap shear properties, resulting in improved mechanical performance of bonded materials since the interfacial bonding has a great influence on the delamination of the structure.

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