Investigation of Joining Dissimilar Materials Using Hot Pressing Process

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Abstract
Hot pressing has been increasingly applied as a joining technology for dissimilar materials because of its simple setup. However, various process parameters must be clearly defined here in order to obtain an optimum joint. In this study, an experimental hot pressing for joining an aluminium alloy sheet grade A5052 with a polybutylene terephthalate (PBT) plate was carried out. Different surface treatment on the aluminium samples were firstly employed by using both mechanical and chemical processes. Then, surface topographies of the treated samples were characterized by scanning electron microscope. The Fourier transform infrared spectroscopy analysis was carried out to examine the C=O in the carbonyl group of thermo-plastic at the joint. During the hot pressing, joining force and temperature were varied. Afterwards, tension shear tests were performed for the aluminium-PBT specimens to evaluate the resulted joint strength. It was found that the pressing force of 1-ton and a pressing temperature of 270°C were the optimum parameters for joining these investigated materials. The maximum joining strength was obtained by specimens subjected to sandblasting combined with chemical surface treatment, in which the surface roughness of aluminium sheet samples was in the range of 4-9 μm. The specimens after shear tests exhibited a cohesive failure. The depth of mechanical interlocking between surfaces of both materials was approximately 33 μm. No change of the molecular structure of PBT was observed by the direct bonding between aluminium and PBT using hot pressing.

Keywords: Dissimilar materials joining, Hot pressing, Surface treatment

1. Introduction
In recent years, joining of dissimilar materials has been increasingly required in the automotive industries due to the purpose of lightweight design, in which saving of fuel consumption and thus environmental protection can be ensured by road transportation. In order to achieve an effective weight reduction of the vehicle with improved structural performance, it is necessary to apply a wide variety of materials. As a result, materials for lightweight structures, for instance, various types of high strength steels, aluminium alloys, plastics and fiber-reinforced composites are more often combined in an
automotive component. Plastics and composite materials can be even used to replace some structural metal parts such as a bumper, front grill, door panel and dashboard. Therefore, new joining technologies for different materials need to be strongly developed [1]. To establish a material joining process between metals and plastics, fundamental researches with regard to many techniques and mechanisms were carried out. Budhe et al. [2] investigated the effect of surface roughness of different adherend material on adhesive bond strength by adhesive bonding. Amend et al. [3] studied influences of laser structuring of metal surface on the joining of aluminium and thermoplastics by means of mono- and polychromatic radiation. Balasubramanian [4] established a relationship between the base material properties and friction stir welding process parameters. Kajihara et al. [5] developed the joining method for polymer-metal hybrid (PMH) by an injection molding process. Kondoh et al. and Hussein et al. [6, 7] studied a direct bonding process of dissimilar materials by using the conventional hot pressing. These processes showed some varying disadvantages depending on used materials and parameters. However, they could provide acceptable joining strength between metal sheets and thermoplastic materials. In most cases, before joining nanostructures or micro-sized holes had to be prepared on the metal surfaces by using either chemical, mechanical or heat-treating process. Most of the results [8, 9] noticed the importance of surface and its positive influence on the joining strength. Due to several types of materials and available specific processes, understanding of welding of dissimilar materials still needs to be enhanced.

In this work, joining between aluminium sheet grade A5052 and PBT plastic was studied using a hot pressing technique. Different surface treatments based on both chemical and mechanical treatments were employed to increase the surface roughness of aluminium sheets. Additionally, joining conditions with regard to pressing force and joining temperature were investigated. The adhesion strengths of hot-pressed samples were characterized by performing lap shear tests. The Fourier transform infrared spectroscopy (FTIR) analysis was also carried out to examine the molecular structural changes of the plastic materials before and after joining to the aluminium sheet.

2. Experiment

In this work, an aluminium alloy sheet grade A5052 with a thickness of 0.8 mm and a polybutylene terephthalate plate including 30% glass fiber reinforcement (PBT-30GFR) with a thickness of 3.0 mm was used. Tensile testing of materials is specified according to European EN 10002 standard. The physical and mechanical properties of aluminium A5052 and PBT-30GFR are presented in table 1.

Table 1. Physical and mechanical properties of aluminium grade A5052 and PBT-30GFR plastic

| Material               | *Density at 25°C (g/cm³) | *Heat distortion temperature (°C) | *Melting temperature (°C) | Tensile strength (MPa) | Yield strength (MPa) | Elongation (%) |
|------------------------|--------------------------|----------------------------------|---------------------------|------------------------|----------------------|-----------------|
| Aluminium grade A5052  | 2.7                      | -                                | 605                       | 240                    | 160                  | 9.96            |
| PBT-30GFR              | 1.5                      | 150                              | 260                       | 96                     | 61                   | 3               |

* Supplier Data Sheet

Test specimens of the hot pressing experiments were prepared according to the standard ISO 19095-2:2015. The dimensions of aluminium and PBT samples were 55×20 mm² and 55×15 mm², respectively, as shown in figure 1. The joining area on both samples was 15x15 mm².
2.1. Metal surface treatment
As the adhesion force between metal and polymer is significantly affected by the nanoscale surface roughness, a surface treatment process for preparing the metal surface is necessary. During such treatment, oil, oxide layers and corrosion layers are also removed and nanoscale surface morphology can be obtained simultaneously [10]. In this work, two approaches were used to generate nanoscale surface structures on aluminium tested samples. First, the nanoscale pattern was created on the aluminium sheet surface by different mechanical treatments, namely, using sandpaper, sandblasting and laser beam [11-13]. The details of each mechanical surface treatment are presented in table 2. Afterwards, chemical treatment [14] was conducted on all samples subjected to each individual mechanical process. Furthermore, a group of samples was only treated by the chemical process.

| Table 2. Mechanical surface treatment process on the aluminium surface |
|-----------------------------------------------|
| Parameters used in the surface treatment process |
| Sandpaper | Grinding with P-240 |
| Sandblasting | 0.5 mm white aluminium oxide particles, pressures 0.3 MPa with a nozzle distance of 5 mm |
| Laser beam | Square texture with a length of 200 µm, laser power of 10 W and frequency of 50 Hz |

By the chemical treatment [15], patterned sheet surfaces were cleaned with methanol for removing the aluminium oxide. The aluminium sheets were then immersed in a solution of 5 wt% NaOH and ultrasonically cleaned for approximately 5 mins. Subsequently, the sheets were dipped in acetone at 25°C for around 30 s to remove the residual NaOH. The aluminium sheets were afterwards immersed in a solution of 25 wt% NH₃, by which the immersing time was varied up to 30 mins and the temperatures up to 60°C were used. Finally, the aluminium sheets were rinsed with water and dried [16]. The aluminium sheet surfaces after treated by each procedure were characterized by scanning electron microscope (SEM). Figure 2(a) shows the surface structures generated by the chemical treatment, while figure 2(b), 2(c) and 2(d) depict those by the combinations of sandpaper, sandblast and laser texturing and the chemical treatment, respectively. It was clearly observed that the aluminium surfaces treated only by the chemical process exhibited randomly distributed shallow holes with the diameters ranging between 10-60 µm. Furthermore, the surface roughness of different samples was measured using a profilometer. The measurements were performed in the longitudinal direction and measuring length was 10 mm in all cases. Hereby, the average profile roughness (Ra) was used to evaluate the roughness of treated specimens. Note that the measuring range of the used profilometer was around 0.77–9.32 µm.
Table 3 provides the mean surface roughness values of prepared aluminium samples. It is seen that the only chemical treatment led to the lowest roughness, while the combination of sandblasting and chemical treatment provided the largest roughness value, which was larger than other combination methods several times.

Figure 2. SEM images of the surface of aluminium samples prepared by (a) chemical treatment, (b) sandpaper, (c) sandblasting and (d) laser beam process

| Surface treatment process | Roughness surface Ra (µm) |
|---------------------------|---------------------------|
| Chemical                  | 0.774                     |
| Sandpaper + chemical      | 1.962                     |
| Sandblasting + chemical   | 9.328                     |
| Laser beam + chemical     | 2.952                     |

2.2 Hot pressing joining procedure
In this work, the aluminium alloy sheet with structured surface and PBT-30GFR sample were joined by a hot pressing process. The hot pressing setup consisted of a hydraulic machine (30 tons capacity), heater including temperature control (up to the maximum temperature of 300°C), punch and die, as shown in figure 3. The temperature at the interface between both samples (Al-PBT) in the middle within the joining area was measured by a thermo-couple until the beginning of pressing.

Figure 3. Schematic of direct bonding between aluminium and plastic using hot pressing
During the experiments, pressing force was varied between 0.5 and 5 tons, joining temperature was set between 240°C and 290°C and the holding time of 60 s was used. Totally, experiments with 36 different conditions were performed in order to investigate the effects of pressing force and temperature. Subsequently, tension shear tests of joined specimens were done on a universal testing machine at the crosshead speed of 2 mm/min. Note that the gripping length at both ends of the sample was 15 mm. Loads and displacements were recorded throughout the tests.

3. Results/findings and discussion

3.1 Effects of joining condition

The joining process parameters, namely, press force and temperature, were investigated with regard to the joining strengths obtained from the tensile shear tests. Note that only the aluminium samples prepared by the sandblasting treatment, which had the highest surface roughness, were here taken into account. The relationship between the pressing force and joining strength was determined and shown in figure 4(a). It can be seen that the maximum strength of the sample between aluminium A5052 and PBT-30GPR was reached at the pressing force of 1 ton. The pressing force less than 1-ton led to samples with insufficient bonding. However, by the press force higher than 1 ton it caused too large deformation of plastic specimens and thus weaker joining. Figure 4(b) presents the effect of joining temperature on the joining strength of samples. Obviously, lower temperatures provided joined samples between aluminium A5052 and PBT-30GPR with lower strengths, because the fluidity of plastic was likely too low to allow for a full penetration in aluminium surface texture. On the other hand, by setting high temperature over the melting point of plastic joined samples showed low strengths, since the plastic already decomposed. Therefore, the joining temperature of 270°C was most suitable for joining aluminium and PBT-30GFR samples using the hot pressing process. An example of a joined specimen prepared by the combination of sandblasting and chemical treatment is illustrated in figures 5.

![Figures 4. Effects of (a) press force and (b) joining temperature on the joining strength](image)

![Figure 5. Joined plastic/aluminium samples after hot pressing prepared by the combination of mechanical and chemical treatment](image)
In addition, the surfaces of aluminium sheet samples in the joining area were observed by SEM. It can be well recognized that the plastics were embedded in the textured grooves of an aluminium sheet prepared by the introduced method, as depicted in figure 6. The adhesion behaviour between both materials was due to the mechanical interlocking, in which the depths of observed interlocks between the surfaces of different samples were approximately 7-33 μm. This interlocking strongly depended on the surface preparation. The largest interlocking depth was observed in the case of sandblasting.

Figure 6. Surface morphologies of bonding areas of aluminium/plastic joined samples prepared by various methods

3.2 Joining strength vs. surface roughness
Figure 7 shows the resulted forces and displacement curves of joined samples between aluminum and plastic prepared by various surface treatments. All tensile shear tests were performed for the samples previously subjected to hot pressing under the temperature of 270°C, 1-ton force and holding time of 60s. It was found that the maximum joining strength of 2.20 kN could be achieved from the sandblasting combined with chemical surface treatment. It was found that this sandblasting treatment caused the highest surface roughness on the aluminium surface. On the other hand, the lowest joining strength of around 0.69 kN was obtained when only the chemical treatment was used. In addition, the correlation between joining strength and surface roughness of different samples was done, as shown in figure 8. The increased roughness of the aluminium surface obviously led to increased joining strengths in a non-linear manner. The surface roughness within the range of 4–9 μm is suggested for the aluminium surface in order to reach an acceptable bonding strength of joined sample in this work. A different trend of resulting shear strengths with respect to the surface roughness was reported by Li., et al. [17]. They showed that samples with higher surface roughness than 4.3 μm exhibited decreased joining strengths. This was likely due to the size of the particle in the sandblasting process was greatly larger than that used in this work. Consequently, joining dissimilar materials certainly needed an appropriate combination of joining process, process parameters and surface characteristic.
Figure 7. Determined force-displacement curves of joined samples between aluminium and plastic after different surface treatments.

Figure 8. Relationship between joining strength and surface roughness of joined samples.

3.3 failure characteristic
To identify the failure behaviour of joined samples after the shear test, the main rupture modes suggested by the ASTM D5573 standard [18] was referred to. Figure 9 shows the interface characteristic taken by SEM of the failed sample subjected to the mechanical and chemical treatments. It can be seen that the sample exhibited a mixed failure mode of interface and cohesive failure.
3.4 FTIR analysis on the plastic of aluminium and PBT-30GFR bonded material

It was reported in [6] that the C=O bond played an important role in the direct bonding of metal to plastics and thus resulting in shear joining strength. The FTIR analysis was thus conducted to detect the change of the C=O spectrum in the bonding area of investigated samples. Three conditions of specimens were hereby taken into account, which was as-received PBT-30GFR sample, PBT-30GFR sample heat-treated at 260°C and PBT-30GFR sample heat-treated at 260°C under 1-ton pressure. This temperature was the joining temperature used in the hot pressing. The results are illustrated in figure 10. The spectrum at the wavenumbers between 2800-3000 cm⁻¹, 1700-1750 cm⁻¹, 1000-1300 cm⁻¹ and 700-990 cm⁻¹ represented alkane C-H group (stretching), C=O bond, C-O and C-H (bending), respectively [19].

It can be seen that for the PBT-30GFR specimens after heat treatment and PBT-30GFR specimens after heat treatment combined with 1-ton pressure no molecular structural change of C=O bond was observed as compared to the spectrum of C=O in the as-received PBT specimen. It meant that the direct bonding between PBT-30GFR and aluminium A5052 by the hot pressing did not cause a change of molecular structure in the examined PBT-30GFR plastic.

Figure 10. FTIR spectrum of (a) as-received PBT-30GFR sample, (b) PBT-30GFR sample heat-treated at 260°C and (c) PBT-30GFR sample heat-treated at 260°C under 1-ton pressure
4. Conclusion
In this work, the joining of aluminium alloy sheet grade A5052 and polybutylene terephthalate with 30% glass fiber reinforcement by means of the hot-pressing process was studied. Both mechanical and chemical surface treatment was applied to form a nanoscale surface structure on the aluminium sheet. Then, roughness measurement and SEM analysis were performed for the prepared sheet surfaces. The influences of joining process parameters resulted in joining strengths from tension shear tests were investigated. The conclusion can be drawn as follows.
- The surface roughness, joining temperature and press force showed significant effects on the joining strength of joined samples.
- The maximum joining strength could be achieved by using the pressing force of 1 ton, joining temperature of 270°C and holding time of 60 s.
- The joining strength of samples obviously increased with an increased surface roughness of the aluminium sheet. The sandblasting combined with chemical surface treatment led to the highest surface roughness and thus provided the largest joining strength. Hereby, the depth of mechanical interlocks between surfaces of both materials was approximately 33 μm.
- The observed failure mode of joined Al-PBT samples was a mixed-mode of interface and cohesive failure.
- No change of molecular structure in PBT-30GFR plastic after direct bonding with aluminium by the hot-pressing process.

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