Hot Press Bonding of Aluminum Alloy AA6061-T6 to Polyamide and Polyamide Composites

Prof. Dr. Moneer H. Tolephih \(^1\), Prof. Dr. Adnan N. Abood \(^2\)\(^,\)\(^b\) and Hussein M. Saad \(^3\)\(^,\)\(^c\)

\(^1\) Al Ayen University.
\(^2\) Engineering Technical College-Baghdad, Middle Technical University.
\(^3\) Mechanical Engineering Department College of Engineering / University of Kerbala
E-mail: \(^1\) monerht@yahoo.com, \(^b\) adnan_naama_59@yahoo.com, \(^c\) husseinmsaad80@gmail.com

Abstract

In this study, aluminum alloy AA6061-T6 was joined by a hot press process with three types of material; polyamide PA 6.6 (nylon), 1% carbon nanotube/PA6.6 and 30% carbon fiber/PA6.6 composites. Three parameters were considered in the hot pressing; temperature (180, 200 and 220°C), pressure (2, 3, 4, 5 and 6 bar) and time of pressing (1, 2, 3, 4 and 5 minutes for 200°C, and 0.25, 0.5, 0.75, 1 and 1.25 minutes for 220°C). Applied pressure has great effect on shear strength of the joint, corresponding to bonding time and temperature. Maximum shear strength was 8.89MPa obtained for PA6.6 at bonding conditions of 4 bar, 220°C and 0.75 minute. For 30% carbon fiber/PA6.6 shear recorded was 8MPa at 4 bar, 220°C and 1 minute, while 1% carbon nanotube/PA6.6 was registered at 8MPa at 4 bar, 220°C and 0.75 minute. Mechanical interlocking of poliamide in anodizing surface is 8\(\mu\)m approximately. The melting point and glass transmission temperature of poliamide and composites are decreased after hot pressing.

Key Words: Aluminum alloy, Polyamide, Hot pressing, Bonding.

1. Introduction

The techniques used to join different materials, especially metals and polymers, are increasingly important in the manufacture of hybrid structures and components for engineering applications. Plastic materials are expected to be more commonly used in automobiles, space, electronic industries due to low weight, great strength, excellent corrosion resistance, thermal insulation, electrical, and flexible design \([1,2]\). In joining fusion processes, the metal part is heated by a heat source, causing the thermoplastic adjacent to the metal interface to melt. The plastic-metal bond is obtained when the plastic solidifies and interlocks with metal surface \([3]\).

In the process of joining aluminum to polymer, the problem occurs that the smooth surface of aluminum results in less wetting of the polymer surface and hence, surface treatment, even chemical or mechanical treatment, is required \([4]\). Mitscgang et al \([5]\) studied the using of pre-treatments during bonding of aluminum /PA6.6. Corundum blasting, and acidic pickling, resulted in joining with higher bonding strength. The shear tensile strength depends on the applied pressure and, therefore, on the flow attitude of the polymer in the joining zone. Holtkamp et al \([6]\) used laser-induced fusion technology to bond metal pins with plastics. Titanium alloy Ti-Al6-V4 and
austenitic stainless steel were heated by laser irradiation and then pressed into polycarbonate and polymethyl methacrylate. The results showed that shear-strength tests of the joint increased with increasing structure density.

Roesner et al [7] studied a new approach to defeating the problems involved in the use of laser radiation to ablate metal surfaces, in order to create microstructures with undercut grooves. The parts are joined in an overlap shape so that an external force can be applied during the heating process, which increases thermal conduction between parts and pushes molten plastic into the surface structures of the metal part. Mechanical interlock of the joint was established and high shear strengths up to 24MPa achieved. Bergmann et al [8] investigated the use of laser to join thermoplastics (PA6.6) with steel thermally, without the help of any additives. The chief process parameters were examined with several joining strategies; laser– transparent and non–nontransparent. For each of the process changes, joint failures within PA6.6 were achieved. It had also been shown that there was no association between the standard surface roughness and shear strength of joining.

Lambiase et al [9] investigated the possibility of using a clinching process to join aluminum and thin sheets of carbon fiber reinforced polymer (CFRP). Split dies with sliding parts were used to make these joints. Mixed joints failed by pulling through the mechanical tests. The taper angle should be kept as small as possible since it has a detrimental effect on the undercut dimension and produces greater delamination in CFRP during the joining process. Increase in punch diameter involved a higher material flow, leading to joints with larger undercuts, on the other hand, it also generated more damage to the CFRP.

The aims of this research can be summarized as:

1 -To study the effect of hot press parameters (pressure, temperature and time) on the shear tensile strength for dissimilar joints of Al/ polymer.

2- To study the mechanism of joining the polymer with the aluminum alloy by anodizing with aluminum alloy surface to form pores, in order to achieve the joining.

3 To assess the influence of bonding parameters on polymer structures and their properties.

4- To investigate the impact of hot press parameters on the failed models of bonding joints.

2. Experimental Work

In this study the materials used were; aluminum alloy AA6061-T6, PA6.6, PA/1% carbon nanotubes and PA6.6/30% carbon fibers. Aluminum alloy and PA samples were prepared from plate with a thickness of 10mm. Dimensions of the samples were 15 * 15 mm.

Before anodizing, the surface of the aluminum was ground and polished. Three variables were used during the hot pressing process; temperature, pressure and time. Selected pressure was 2, 3, 4, 5 and 6 bars, while the time was 0.25–5 minutes and temperature 180, 200 and 220°C. Five samples for each variable were tested.
The samples were examined using optical microscopy, Fourier transform-infrared spectroscopy (FTIR), energy dispersion spectral (EDS), thermal gravity analysis (TGA) and differential calorimeter scanning (DSC). A single shear test was conducted by compression test machine. The anodizing process was carried out under a current density of 200A/m², temperature at 25°C and sulphuric acid 15%wt for 60 minutes.

3. Results and Discussion

3.1 Aluminum to PA6.6 Bonding

For pressure 2 to 6 bar and time 1 to 5 minutes at 180°C, no bonding was registered. This can be attributed to the fact that the polymer lacked sufficient time to melt and to generate good mechanical interlocking. When the temperature was increased to 200°C, bonding was achieved at 1, 2, 3, 4, and 5 minutes, at a certain pressure. At pressure 1 bar, bonding did not occur because the PA did not penetrate the pores of the anodized aluminum to a sufficient extent. A good polymer penetration was achieved at sufficient pressure of 6 bar and time of 1 and 2 minutes (Figure 1).

Two types of failure mode were seen; an interfacial shear failure mode occurred at the interface of the joint, while other fails occurred in polymer with higher shear strength. The maximum single shear recorded was 8.89MPa at 6 bar and 2 minutes. Increasing the bonding time to 5 minutes resulted in single shear reduced to 4.89 MPa associated with polyamide distortion.

Increasing the applied pressure can cause a mechanical deformation within the molten layer of polymer. It can be concluded that additional heating is required to augment molten polymer sufficiently to fill the pores. At 220 °C, PA undergoes deformation for times greater than 2 minutes. Periods of 0.25, 0.5, 0.75, 1 and 1.25 minutes were selected and adopted. At 220°C, all tested specimens were joints at all selected pressures and times, except at 0.25 minute and 2 bar (Figure 2). When the time was raised to 0.75 minute, shear strength increased to 8.89MPa at 4 bar.
Table 1.

| Parameter | Unit | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
|-----------|------|---|---|---|---|---|---|---|
| Temp.     | C    | 200 | 200 | 200 | 200 | 200 | 200 | 200 |
| Pressure  | Bar  | 2 | 3 | 4 | 5 | 6 |  |  |
| Time      | Min  | 1 | 2 | 3 | 4 | 5 | 6 | 7 |

In general, single shear strength increased with increased pressure until it reached maximum value, then decreased. Molten PA did not find more empty pores to fill and flowed out with augmentation of polyamide deformation. For 220°C temperature, the effect of pressure is recognized where the highest pressure value shows a complete penetration for the molten polymer in contrast with values of the lowest pressure. Maximum tensile strength, 8.88MPa of Al/PA6.6 joint, was obtained at 200°C, 6 bar and 2 minutes and at 220°C, 4 bar and 0.75 minute. Results agree with F. C. Liu et al [11] whose study used friction lap welding when bonding aluminum alloy AA6061 and MC Nylon 6; the shear strength of 5–8MPa was recorded over a wide range of welding parameters.
3.2 Aluminum to Carbon-Fiber PA6.6 Composite Bonding

At a temperature of 220 °C, pressure of 2, 3, 4, 5 bar and for five periods (0.25, 0.5, 0.75, 1 and 1.25 minutes), bonding occurred for all conditions. However, when temperature was reduced to 200°C, bonding did not take place. Carbon fibers with 30% lowered adhesion between PA and aluminum. The size of the carbon fiber size is larger than the size of the pores of the anodizing layer and they were not plasticized. At a temperature of 220°C, in general, shear strength decreases with increasing applied pressure after a specific time (Figure 3).
Figure (3); Shear strength of Al/PA 6.6 composite

Minimum shear strength was recorded at maximum applied pressure and maximum time (4.45MPa at 6 bar and 1.25 minute). Shear strength increased gradually with time until it reached its maximum value (7.78MPa) at 1 minute with 4-bar pressure. Shear strength behavior for Al/carbon fiber-reinforced PA6.6 joint was somewhat similar to that of Al/PA6.6, in which shear reached a maximum value then dropped. At low pressure (2 bar), carbon fiber-reinforced PA6.6 partially penetrated into pores of the anodized layer. The penetration was increased with the increased applied pressure until pore filling was attained. Maximum shear strength (7.78MPa) of Al/carbon-fiber PA6.6 was recorded at 220ºC, 4 bar and 1 minute. These results agree with Mitschang [12], when using induction heating to bond AlMg3 with carbon fiber reinforced nylon 6,6.

3.3 Aluminum / Carbon nanotube CNT's Reinforcing Nylon 6.6 Bonding

Two temperatures (200°C and 220 °C), five levels of pressure (2, 3, 4, 5 and 6 bar) and five periods of time (0.25, 0.5, 0.75, 1 and 1.25 minutes) were used. In general, shear strength with time had the same attitude (Figure 4). Minimum shear strength was recorded at minimum applied pressure (3.56MPa at 2 bar and 1 minute). Shear strength increased with time until reaching its maximum value (8MPa at 2 minutes and 6bar) and then reduced. Shear strength behavior for Al/CNT's reinforcing PA6.6 was similar to that of Al /PA6.6, but at pressure of 6 bar, the
composite flowed out. When the temperature was increased to 220°C, maximum shear force was 8MPa with applied pressure of 2 bar and 1 minute, while the minimum shear strength of 3.5MPa was recorded under 4 bar and a period of 1.25 minute (Figure 5). At pressure 2 bar, shear strength increased with time until it reached maximum value (7.78MPa at 1.25 minute) and then decreased. At pressure 4 bar, shear strength reached peak value (8MPa) at 0.75 minute. Bonding of Al/PA6.6 exhibited slightly higher shear strength (8.89MPa) at 220°C, 4 bar and 0.75 minute as compared with those of Al/CNT-reinforced PA 6.6 (8MPa at 220°C, 4 bar and 0.75 minute). Addition of CNTs restricted the penetration of molten polymer into anodizing pores. Bonding of Al/PA6.6 exhibited higher shear strength, also, compared with those of Al/carbon fiber-reinforced PA 6.6 (7.78MPa at 220°C, 4 bar and 1 minute).
Figure (5); Shear strength of Al/ CNT-reinforced PA 6.6 at 220°C

SEM examination indicated a bonding area with depth of 8μm approximately (Figure 6). This depth was further affected by temperature, pressure and time [12]. There was no air pocket at the interface because the polymers had completely melted – otherwise, the pocket forms.
Figure (6); SEM image of joining PA6,6 at 6 bar, 2 minutes

3.4 Characterization of Bonding Interfaces

The EDS line map provides helpful information about the bonding interface. The presence of carbon, oxygen and aluminum is a function of the penetration of molten polymer into the pores of anodizing layer (Figure 7). An interfacial transition layer between polymer and A6061 has been produced with lower concentrations of carbon, aluminum and oxygen. These results agree with Zhou Zhang et al [13].
Figure (7); EDS map line of PA and Al joint (a) carbon (b) oxygen (c) aluminum
DSC and TGA testing showed that the melting temperature of PA 6.6 and their composite went down slightly after hot pressing. The main reason for the reduction was crystallite decline due to oxidation [14]. From Figure 8, we can see the $T_g$ temperature starting from 205°C while for bonded sample it was 158°C. The melting point for PA before bonding was 204.3–229°C, reducing after hot pressing to 198.7–211.1°C. The point of reaction and peak maximum were (-41.113Mw) at 215°C and (-42.981mW) at 218.7°C, which increased during hot pressing to (-16.972mW) at 210°C and (-17.627mW) at 213.3°C.

Enthalpy (-45.6 J/g) increased after hot pressing to (-22.6 J/g). Results showed that there were three reaction regions for pure PA 6.6, these three regions shifted and changed their areas when polymer was exposed to heat. There were two mass changes for pure PA 6.6 because it is made from two monomers, each containing 6 carbon atoms, hexamethylenediamin and adipic acid. Before joining the first mass change was -42.68% (377.6°C) and second was -43.5% (559.85°C). After joining, the first mass change was -8.87% (369.57°C) and second was -48.74% (527.26°C). The 1% CNT-reinforced PA 6.6 showed almost the same behavior of PA6.6 for TGA. The $T_g$ temperature started from 218.6°C while for bonded sample it was 122.2°C. The melting temperature was found to be decreased from 213.9–235.4°C to 212.2-235°C (Figure 9). The point of reaction and peak maximum were (-23.04mW) at 222.8°C and (-25.2mW) at 226.3°C respectively, reducing for the bonding sample to be (-32.04mW) at 220.4°C and (-34.684mW) at 225.3°C.

Enthalpy (-60.08 J/g) increased after bonding (-49.98 J/g). Mass also changed, before joining the first mass change was -29.99% (373.16°C) and the second, -69.72% (593.43°C). After joining the first mass change was -47.5% (372.13°C) and second was -47.92% (493.8°C). The same behavior was observed for 30% carbon fiber-reinforced PA 6.6, the $T_g$ temperature starting from 238.7°C while for the bonded sample it was 163°C. The melting temperature was found to be decreased from 211.1-233.6°C to 206.6-236.4°C (Figure 10).
Figure (8); DSC & TGA chart of PA6.6 (a) before joining (b) after joining
Figure (9); DSC & TGA chart of 1% CNT-reinforced PA6.6 (a) before joining (b) after joining
Figure (10); DSC & TGA chart of 30% carbon fiber-reinforced PA6.6
(a) before joining (b) after joining
Conclusions

The main conclusions drawn from this experimental work, analysis and discussion can be summarized as:

1- Maximum shear tensile strength (8.89MPa) of Al/PA 6.6 was recorded at 220ºC, 4 bar and 0.75 minute, while Al/carbon-fiber PA 6.6 and Al/CNT's PA6,6 slightly less shear were register.

2- Temperature and pressure parameters had a major effect in joining of Al/PA 6.6 and its composites, while the time parameter had a limited effect.

3- Existence of carbon, oxygen and aluminum at bonding interface confirmed the penetration of molten polymer inside the pores of the anodizing layer.

4- Tg temperature slightly reduced during hot pressing for PA 6.6 and its composites.

5- Two types of failure mode occurred in the joining of Al/PA 6.6; the first was interfacial shear failure at the bonding area and second at the polymer side.

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