Joining of Double Pre-Holed Aluminum Alloy AA6061-T6 to Polyamide PA using Hot Press Technique

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Abstract. The objective of this work is using a hot press technique to join a hybrid structure of aluminum alloy AA6061-T6 sheet of 1mm thickness together with polyamide PA sheet of 2mm thickness. The aluminum alloy specimen was pre-holed with two holes of 5mm diameter. The joining process was carried out with a lap joint configuration. Three different process parameters of the joining process were used: temperature (164, 172 and 180°C), pressure (4, 7 and 10 bar) and time (1, 2.5 and 4 min.). The joints were tested by a shear test, macrostructure and scanning electron microscope (SEM) inspection. The design of the experiments (DOE) method was used to analysis the effect of the process parameters on the joint shear force. The DOE optimized the shear force of the joint with a maximum value of 1565 N at 177.5°C 4bar and 3.5min. The SEM examination indicated that the joining mechanism occurred by re-solidified the PA through the internal surface of the aluminum hole.

Keywords: AA6061-T6, Hot press, joining, polyamide PA, hole, DOE.

1. Introduction

Nowadays it is become a necessary to produce lightweight dissimilar materials having high corrosion resistance, strength, conductivity and toughness. Therefore, it was resorted to joining different materials as hybrid structures of polymers / metallic alloys [1-3]. The joining process of hybrid structures between polymeric and metallic materials is important in many engineering applications such as medical, automotive, aerospace and biological industry [4,5]. The hybrid structures are consisting of dissimilar materials having light weight such as polyvinyl chloride, polyethylene or fiber reinforced polymers that it's joined with aluminum, stainless steel or magnesium alloys [6, 7]. There are many joining processes that use to join the polymer to the metal such as friction spot welding [8], laser direct joining [9], adhesive bonding [10], ultrasonic staking [11], injection clinching joining [12] and hot press bounding process [13]. Due to the different physical and mechanical characteristics between the metal and the polymer, so it is difficult to join these materials [11].
There are many studies about facilitates of the joining process of hybrid polymer to the metal. It concluded that: in order to join the polymer and metal, its need to pre-treat the metal surface. The type of joining mechanism between the metal and the polymer is either chemically bonded with adhesives or mechanically by interlock. So, to improve strength, the roughness of surface is very important to be taken into consideration due to the size and density of the surface roughness and the size and depth of the pores at the surface of the metal. The anodizing process of the metal surface was used to increase the size of pores at the oxide aluminum surface which increase the amount of molten polymer in the anodized surface and the joint strength. Also, mechanical (scratch) of the metal surface method, the laser method, or a drilling the metal method (in which, the hole filled with polymer) were used to enhance the joint quality [14-19].

Aluminum AA5052 was joined to composite sheets of short-carbon-fiber-reinforced polypropylene (PP-SCF) by using refill (Threaded Hole) friction spot welding (THFSW) [20]. Aluminum AA5754 sheets were joined to a composite material of a thermoset matrix composite included of carbon fibre reinforced epoxy resin (CF-epoxy) by using ultrasonic metal welding [21]. The hybrid structure is performed by joining the technical thermoplastics (PC, PA6, PA66-GF30) with aluminum (EN AW-5182) using the laser surface metal method [22]. Friction press joining (FPJ) method was used to join the aluminum with glass fibre reinforced polyamide by applying the laser to make a surface pre-treatment of metal before the joining process [23]. A process of hot press binding was applied to join the metal with the polyamide 6 (PA6). When the metal reached the elevated temperature, the surface of polymer melted and wet the metal surface [24].

The objective of this work is to join the hybrid structure (AA6061-T6 with polyamide PA) by a hot press bonding process. The aluminum alloy specimen was pre-holed with two holes and arranged with polymer in a lap joint configuration. The effect of hot press parameters (temperature, pressure and time) on the mechanical properties of the joint was studied. A design of experiment method was used to arrange and analysis of experiments and study effect of the process parameters on the shear force of the joint and to optimize the process parameters. Also the optimum joining parameter was analyzed by macrostructure and scanning electron microscope (SEM).

### 2. Experimental Setup

#### 2.1. Materials

The hot press bonding process was used to joint two types of materials: aluminum alloy AA6061-T6 with polyamide (PA). The mechanical properties and chemical composition analysis of aluminum alloy AA6061-T6 are illustrated in tables 1 and 2, respectively, the polyamide had a melting point Tm=177°C.

| Property          | Yield Point \( \sigma_u \) (MPa) | Tensile Strength \( \sigma_y \) (MPa) | Elongation EL% |
|-------------------|----------------------------------|--------------------------------------|----------------|
| Nominal [25]      | 240                              | 290                                  | 10             |
| Actual            | 256                              | 315                                  | 13             |

Table 1. Mechanical properties of AA6061-T6
Table 2. Chemical composition of AA6061-T6

| Element | Si   | Mn  | Mg   | Ti   | Cr   | Cu   | Fe   | Zn   | Al   |
|---------|------|-----|------|------|------|------|------|------|------|
| Nominal value [25] | 0.4-0.8 | 0.15 | 0.8-1.2 | 0.15 | 0.04-0.35 | 0.15-0.4 | 0.7 | 0.25 | Remainder |
| Actual value | 0.65 | 0.11 | 1 | .11 | 0.25 | 0.2 | 0.4 | 0.17 | Remainder |

2.2. Specimens Preparation
A 1 and 2mm thickness were used for the aluminum alloy (AA6061-T6) and polyamide (PA) specimens, respectively. According to the standard specification (AWS spot welding C1.1M/C1.1:2012). Many specimens were manufactured with a length of 100mm and a width of 25mm, while the dimensions of lap joint were 25 x 25mm² [26]. Two holes were machined in the aluminum specimen in the middle of the lapped area. Each hole was manufactured with a diameter of 5mm. The distance between the holes was 10mm, as shown in Fig. 1.

2.3. Joining process and hot press equipment
The joining process was occurred by hydraulic press equipment with the aid of heater device. The applied pressure was applied and regulated by the hydraulic press controller as shown in Fig. 2. The temperature was regulated by a temperature controller. This equipment contained a heater of Tmax = 400°C and a hydraulic press with a 15 ton capacity. Moreover, a die fixture device was used to fix the aluminum and polymer specimens. The heating device contained the source of heat and the two plates (lower and upper plates). The heater device was inserted between the upper and lower plates. A K-type thermocouple was used to measure the temperature during the joining process. The thermocouple was put in the middle of the bottom surface of the lap joint of the aluminum alloy. A suitable die was designed consisting of two parts: the first was copper and the second was a special kind of wood to obtain a joint center line and prevent the slide of specimens. Copper metal was used to transfer the heat from the heater to the aluminum specimen by conduction. The wood specimen was used to insulate the joint thermally in order to prevent the heat loss during the joining process. The specimen of polyamide was placed over the aluminum through the slot of the die. The load was applied directly on the aluminum alloy specimens. The heating device heats the polymer with a temperature around the melting point of the polymer. The combined action of heat and pressure joined the two materials by penetrating the melting polymer through the aluminum holes.
2.4. Taguchi Design

The design of experimental method (DOE) was used according to the Taguchi approach to study the effects of the process parameters on the joint quality. The pressure, temperature and process time are the most important factors that directly affect the amount of shear force of the joint [3]. The main joint parameters consisted of three levels for each joint parameter to investigate the shear force, as illustrated in table 3. Taguchi method was applied with L9 orthogonal array for the design of experiments. Nine experiments were designed according to the Taguchi method with respect to the levels of each parameter as illustrated in table 4.

| Table 3. Levels of Joint Parameters |
|-----------------------------------|
| Joint Parameters | Levels |
|------------------|--------|
| Temperature (°C) | 164    |
| Pressure (bar)   | 4      |
| Time (min.)      | 1      |
|                  | 172    |
|                  | 7      |
|                  | 2.5    |
|                  | 180    |
|                  | 7      |
|                  | 4      |
|                  |        |

| Table 4. Joint parameters according to Taguchi method |
|---------------------------------|
| No.    | Temperature (°C) | Pressure (bar) | Time (min.) |
|--------|------------------|----------------|-------------|
| 1      | 180              | 4              | 1           |
| 2      | 180              | 7              | 2.5         |
| 3      | 180              | 10             | 4           |
| 4      | 172              | 4              | 2.5         |
| 5      | 172              | 7              | 4           |
| 6      | 172              | 10             | 1           |
| 7      | 164              | 4              | 4           |
| 8      | 164              | 7              | 1           |
| 9      | 164              | 10             | 2.5         |

The joined specimens are shown in figure 3.
2.5. Experimental Tests
The shear test, optical macrostructure test and scanning electron microscope (SEM) inspection were used to test the joined specimens. The standard “AWS spot welding C1.1M/C1.1:2012” was adopted to prepare the tensile shear test specimens [26]. In order to prevent slipping and bending during the tensile test, a shim was placed at the ends of each specimen in the opposite sides as in Fig. 4. The cross head velocity of the tensile shear test was 10 mm/minute. During the macrostructure and (SEM) inspections, the specimens were dealt with wet grinding using SiC emery papers with different grits size p (600, 800, 1000, 1200 and 2000) according to the standard ASTM E 407-99 [27]. The polishing process was performed with different particle size of alumina (3, 0.3, and 0.05) µm. A special cloth was used at 180 RPM. The mirror was obtained by washing with water and alcohol, hence the specimens were dried with air. The macrostructure and (SEM) test were used to examine the microstructure of the cross section joint and indicate the interface of the joint.

Figure 3. Experimental joint specimens of PA-AL.

Figure 4. The shear test equipment: a) Experimental equipment & b) schematic of the test
3. Results

3.1. Shear Tensile Test
According to the designed levels of the joining parameters, all the specimens were successfully joined by the hot press method. Also, all the samples were successfully tested by shear force test. Shear tests indicated that all the samples had a shear force value, which varied from sample. Figure 5 shows the shear force values of the samples according to the sample number of table 4. The sample 8, which joined at the temperature 164°C, applied pressure of 7 bar and time of 1 minute, exhibited the minimum shear force value (470N). The maximum shear force value (1490N) was observed in the sample 4, which joined at temperature 172°C, applied pressure of 4 bar and time of 2.5 minute. Low shear force values of the tested samples can be attributed to the insufficient input heat during the joining process. The sufficient input heat and applied pressure increased the penetration of the molten polymer through the aluminum surface, which accordingly increased the joint shear strength and prevent the polymer pull out at the interface surface. In the samples 1, 2 and 3, the applied pressure and time increased gradually, as a result the shear force of those samples is increased gradually. Increasing the processing time increased the input heat, which increased the amount of the molten and penetrated polymer in aluminum.

![Figure 5. Results of shear force of all samples](image)

Figure 6 shows the tested samples that failed at different regions at the interface between the aluminum sheet and the re-solidified polyamide. All the tested samples were failed at the polymer side. Two modes of failure were observed in the polymer specimen: shearing and fracturing the polymer material. In the samples that joined with a sufficient heat and pressure, a strength joined was observed between the two materials. Those samples were failed by two types of failure mode: shear and fracture the polymer as shown in samples 3, 4, 5 and 9. A little amount of input heat and/ or applied pressure resulted in joining the sample with a week join interface between the two materials. Those samples were failed by shearing the polymer at the holes region, as shown in samples 1, 2, 6, 7 and 8.
3.2. DOE

3.2.1. The Main Effect Plot
Taguchi analysis was performed using Minitab software to analyze the effect of joining parameters on the shear force of lap joint and determine the optimal level of parameters that give the best shear force, as shown in Figure 7. The results indicated that all the process parameters have an alternative effect on the shear force of the joints according to its levels. The shear force was increased by increasing the temperature from 164 to 172 °C, pressure from 7 to 10 bars and time from 1 to 2.5 minutes. The other levels of the processing parameters decreased the shear force of the samples. The main effect plot determined the optimum process parameters that give the optimum shear force of the joint at temperature 172 °C, pressure 7 bar and time 2.5 minutes.

3.2.2. The Interaction Plot
In order to study the interaction effect of each two process parameters on the shear force of the joint, an interaction plot was graphed according to the DOE from the MINITAB program, as shown in Figure 8. The results indicated the following effects:
1- For the interaction between the pressure and temperature, increasing the applied pressure decreased and increased the shear force of the joints at 172 and 180°C, respectively.
2- For the interaction between time and temperature, increasing the process time increased the shear force of the joints at 180°C only.
3- For the interaction between the pressure and time, increasing the process time increased the shear force of the joints at 7 and 10 bar.

![Interaction Plot for the joining parameters](image1)

**Figure 8.** Interaction Plot for the joining parameters

3.2.3. *Contour Plots*

A contour plot is graphed to illustrate the variation of the shear force of the joints with respect to each two parameters, as shown in figure 9. The results indicated the following effects:
1- For the interaction between the pressure and temperature, regardless of temperature, the minimum shear force values occurred at 7 bar. The shear force values of the joints occurred at minimum and maximum applied pressure.
2- For the interaction between the time and temperature, the shear force of joints increased by increasing both of the processing temperature and time.
3- For the interaction between the pressure and time, the maximum shear force values occurred at minimum and maximum applied pressure.

![Contour plots of shear force](image2)

**Figure 9.** Contour plots of shear force
3.2.4. Regression Equation

According to Taguchi method, a mathematical equation of the joint shear force (regression equation) was obtained in term of the process parameters. The regression equation is obtained to find or predict the theoretical shear force value at different joining parameters, as follows:

Shear Force (N) = 4.3 Temperature (°C) + 39.2 Pressure (bar) + 138 time(min.)

3.2.5. The Optimal Parameters

The results of the shear force of the joints were analyzed by the Taguchi method with the aid of the Minitab program to find out the optimum joining parameters that maximize the joint shear force. Table (5) shows the optimizer parameter analysis from the DOE for shear force. The theoretical value of shear force was 1638 N according to the DOE analysis. The polymer was joined with aluminum according to the processing parameters in table 5. The sample was tested and the shear force value was 1565 N. A good agreement was obtained between the theoretical and experimental results with an approximate error of 4%.

| Temperature (°C) | Pressure (bar) | time(min.) | Shear Force (N) |
|-----------------|----------------|------------|-----------------|
| 177.5           | 4              | 3.5        | 1638            |

3.3. Macrostructure and scanning electron microscope (SEM) inspections

The sample of optimum shear force, No.4, was examined by the macrostructure and SEM inspections to analyze the type of interface between the two materials, AA6061-T6 and polyamide. Figure 10 shows the cross-section of macro-structural zones of the joint, which included the base materials, holes and re-solidified polyamide inside the holes. The polyamide flowed through the holes and the aluminum surface in the lap joint due to the high temperature and pressure applied. It seems that the molten polyamide was penetrated into the holes and the aluminum surface and filling it’s due to the higher temperature and applied pressure. The test of SEM was performed to indicate the thickness of the interface layer between the two materials that determine the behavior of the joining mechanism at the interface line, as shown in figure 11. The interface line width was varied along the aluminum surface with an approximate range of 13-29μm, which represents a good interface width [28]. The SEM image indicated that the interface between the aluminum and re-solidified polyamide occurred with mechanical interlock between the two materials.

![Figure 10. Macrostructure of the sample 4](image-url)
4. Conclusions
A hot press process was used to join aluminum AA6061-T6 with polyamide (PA). Two holes were placed on the side of aluminum. The effect of pressure, temperature and time of the process on the joint shear force were studied. The following conclusions were recorded:
1- The hot press technique is a successful method to join the AA6061-T6 to PA
2- The minimum shear force of the joint (470N) occurred at temperature 164°C, a pressure of 7 bar and time of 1 min.
3- The maximum shear force of the joint (1490N) occurred at temperature 172°C, applied pressure of 4 bar and time of 2.5 min.
4- The samples of small shear values were failed with shearing the polymer at the holes in AA6061-T6.
5- The samples of high shear values were failed with shearing and fracturing the polymer at the holes in AA6061-T6.
6- The shear force of the joint was optimized to a value of 1565N by the DOE method.
7- The optimized shear force exhibited a good agreement with the experimental value with an approximate error of 4%.
8- The heat input and/or the applied pressure had the highest effect on the joint failure mode and shear force value.
9- The SEM examination indicated that the joining mechanism was occurred by a mechanical interlock between the two materials.
10- The interface line width of the joint had a range of 13-29μm.

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