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Joining of Aluminium Alloy AA6061-T6 to PVC Polymer by Friction Stir Lap joining Process

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Abstract: The aim of this research is to join sheets of aluminium alloy AA6061-T6 of 1.5 mm thickness with polymer polyvinyl chloride (PVC) of 4 mm thickness by a friction lap technique. Drill holes of 3, 4 and 5 mm were produced in the AA6061 specimens and a lap joint arrangement was set up with the PVC sheet. Six parameters were used in this technique: hole diameter, tool diameter, number of holes, rotating speed, linear speed, and tool plunging depth. The shear test results at the holes were analyzed by a Minitab program with the aid of the Taguchi method. IR thermometer was used to measure the temperature distribution at the joint. The results indicated that all the samples failed with shearing the PVC at the aluminium hole without dislocation the polymer. The maximum shear force is 1850N. The joint shear force increased by increasing the plunging depth and rotation speed of the tool and decreased by increasing the hole numbers and diameter of the aluminium specimen. The hole diameter beside the rotating and the linear speed exhibited the highest effect on the joint shear strength. The developed temperature during the joining process was an effective parameter on the joints quality. The SEM tests indicated that the joining between the aluminium and polymers occurred by a mechanical interlocking at the common surfaces.

1. Introduction

Nowadays, the engineering employment of modern thermoplastic in an automobile, aerospace manufacturing, electronics industries, and transportation industries are raised. This is because of their acceptable characteristics: lightweight structures, high qualitative strength, stiffness along with excellent corrosion resistance, thermal and electrical insulation, environmental stability, great fatigue execution and easy fabrication treatment at comparatively inexpensive [1]. Specifically, determination and improvement of the light materials (for example magnesium, aluminium and the polymers) can fundamentally result in a detrimental in the weight of the vehicle. In the modern group of vehicles, aircraft machines, and the present project of hybrid form in which different types of materials (polymers or metals) are available, regularly demands to join the parts by the friction joining technique [2]. High toughness, good heat, and electrical accessibility are among the combined characteristics in lightweight metals (such as aluminium).

The polymers display appealing strength-to-weight proportion, corrosion impedance, and isolation properties [3]. Friction lap welding that is advanced in JWRI, Osaka University [4], is considered as new concept of joining the procedure of metal to plastic for hybrid joints. A non-consumable rotation tool is compressed on the surface of the metal matrix and transports long the overlap joint region. The FLJ process is similar (in mechanism) to the friction stir welding (FSW) [5, 6]. The major difference between the FLJ and FSW are that the FLJ tools don't have a stir pin, and subsequently, the main function of the rotating tool not to flow materials around the pin, but to press and heat the metal specimen. The heat is



developing by the friction between the tool and the metal. The heat is transmitting by conduction phenomenon from the heated metal to the polymer and then melts the polymer in a narrow zone which is adjacent to the joint interface line. The bonding zone between the plastic and metal can be executed after the solidification of the molten polymer under the applied pressure which provided by the pressed metal. The structures of the polymer-metal are more troublesome to join by conventional mechanisms, generally because of their large difference in physically, chemically and mechanical features between them, therefore, the limited joining techniques accessible to this kind of hybrid material [7, 8].

In this work, aluminium alloy AA6061 was used to be joined with polyvinyl chloride (PVC), the two materials were joined using two sheets of different thickness. A friction stir lap joining technique was used to achieve the process with the aid of rotating tool without pin. Initially, the AA6061 was holed with a number of holes along the joining line, which put over the polymer. The principle of joining is that to produce a composite material between the metal chips and the melted polymer during the joining process. The joint properties have been analyzed using different hole diameter. The shear force, microstructure, macrostructure, scanning electron microscopy (SEM), and energy dispersive spectroscopy (EDS) of the joints were investigated.

2. Experimental Procedure

2.1. Materials and specimens preparation

Aluminium alloy AA6061-T6 (1.5 mm thick) and PVC (4mm thick) with sheets dimensions of 200× 100 mm were prepared, as shown in figure 1. The chemical composition of the aluminium alloy specimen (AA6061) is listed in table 1 and the mechanical and physical properties for each material are listed in table 2. The drilled diameter holes (3, 4, and 5 mm) were manufactured in aluminium specimens to achieve the joining and prevents the dislocation of the melted PVC from the AA6061 samples during the shear test.

2.2. Joining process

The joining process was carried out by two stages: initially, by melting the polymer components at the region near the hole of the aluminium specimen. The molten, polymer was penetrated the through the hole by the applied pressure of the tool. The joining process has been done by using the milling machine, as shown in Figure 2. A cylindrical HSS tool of 12 mm diameter was utilized to preheat the samples, develop the heat required to make the polymer in a molten state and applied the pressure to penetrate the molten polymer through the hole in aluminium alloy specimen.

Primarily, the linear and the rotating tool speed cause the preheat of the samples and generates the heat at the connection region with the upper surface of aluminium which leads to increase the temperature at the lap joint and melts the PVC work piece by the friction process between the two surfaces.

The applied pressure was carried out by moving down the rotating tool with a specific depth of 0.05, 0.1, and 0.2mm. During this step, the temperature is increased gradually and then the molten polymer penetrates up through the holes, which build the composite material from AA6061 fragments with molten PVC as shown in figure 3. The fragments of the aluminium specimens are clearly observed. The images indicated that the holes of the aluminium specimen were filled with a mixture of the molten polymer with the aluminium fragments to produce a composite material at the joined region.

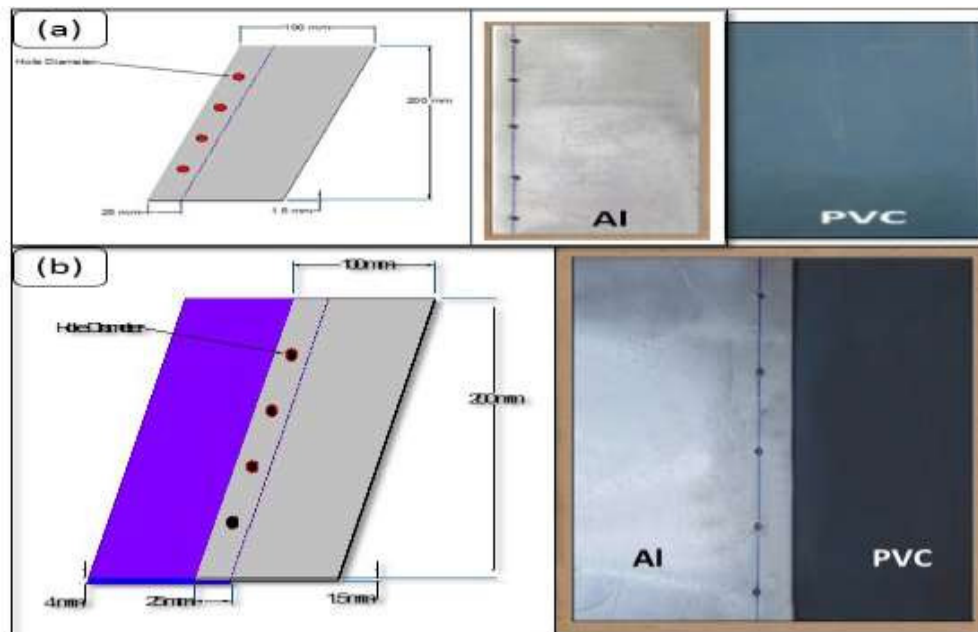


Figure 1. The manufactured samples of AA6061 and PVC. (a) AA6061 with five holes and PVC Specimens , (b) lap joint configuration.

Table 1. Chemical composition of the AA6061-T6.

Element wt.%	Si	Ti	Zn	Cr	Mg	Mn	Cu	Fe	Al
Standard Value ASTM B209	0.4- 0.8	0.15	0.25	0.04 - 0.35	0.8 - 1.2	0.15	0.15 - 0.4	0.7	Rem.
Measured Value	0.594	0.055	0.025	0.181	0.871	0.10-4	0.23-2	0.406	Rem.

Table 2 . Mechanical and physical properties of the materials

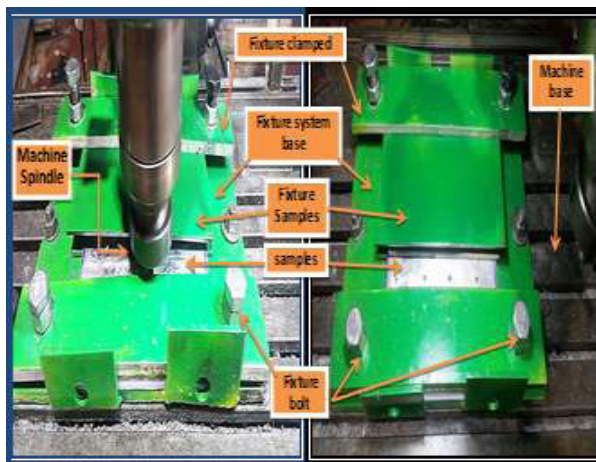
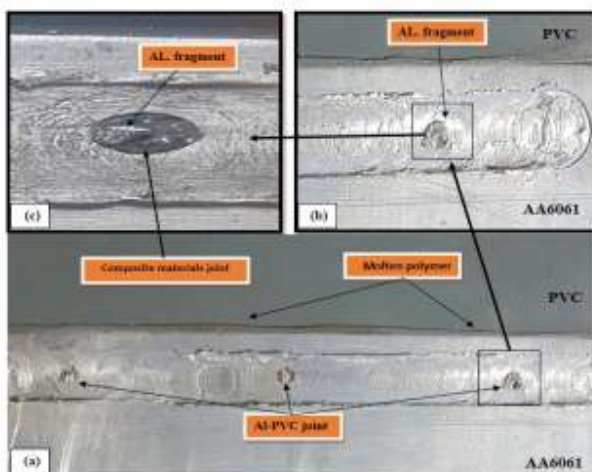
	Yield Strength MPa	Tensile Strength MPa	Elongation%	Thermal Conductivity W/(m.K)	Density g/cm ³
AA6061-T6	275	310	10-12	167	2.7
PVC	30-50	40-60	8-25	0.16	1.35-1.5

2.3. Design of the experiments

The design of the experiments (DOE) parameters was done using statistical software (Minitab) by a Taguchi method to analysis the effect of these parameters on the joint quality. Table 3 outlines the experimental levels of each parameter for joining the aluminium to polymer specimens. The plan of this work is to study the effect of machine joining parameters on the joint strength. Three process parameters were: rotational speed, transverse welding speed and plunging depth. The effect of the hole diameter and numbers in the aluminium specimens were studied A total number of nine samples of the dissimilar materials (PVC and AA 6061) were used to join it together using the friction process according to the DOE.

Table 3 .The experimental levels process parameter for joining PVC with aluminium.

Sample NO.	Tool dia. (mm)	Hole dia. (mm)	Hole No.	Linear Speed (mm/min.)	Rotating Speed (RPM)	Tool Depth (mm)
1	12	3	4	80	800	0.1
2	12	3	4	80	1000	0.2
3	12	3	4	80	1200	0.05
4	12	4	5	40	800	0.1
5	12	4	5	40	1000	0.2
6	12	4	5	40	1200	0.05
7	12	5	3	60	800	0.1
8	12	5	3	60	1000	0.2
9	12	5	3	60	1200	0.05

**Figure 2.** Milling machine and joining fixture setup.**Figure 3.** Joined samples of Al to PVC.

3. Results and Discussion

3.1. Shear tensile test

Shear tensile test of the joined samples has been done by a tension test instrument. The overall joint samples dimensions were: 25mm wide and 175 mm length, where the lap joint assembly was prepared in which the overlap region dimensions were 25 X 25mm according to the AWS resistance spot welding specifications, as shown in Figure 4.

The aim of the shear test is to determine the shear strength of the joint area. The test has been carried out according to ASTM D638[9]. The shear test values of the samples are illustrated in table 4. The maximum shear force was recorded with values of 1850, 1833, and 1825N in the samples 2, 8 and 9, respectively. It was recorded that the small diameter of the hole (3mm) exhibited the best shear strength that used to join this type of materials.

Figure 5 represents the experimental shear force data for the nine samples of the joints, with different joining parameters. The behaviour of the shear forces for each hole in all samples and the highest and lowest shear force can be observed at any point of the holes. The highest shear forces recorded in the first and second holes are observed in the samples 7, 8 and 9, while the highest shear force occurred in the hole 3 is observed in the sample 2, with a value of 1850 N. For the hole 4, the highest shear force was recorded in sample 2 and 3; however the highest shear force occurred in the sample 4 and 6 for hole 5.

In contrast, the lowest shear force was recorded in all holes of the sample 5 which ranged from 308-664 N. This samples recorded low shear force due to the high input heat at the joined area during the joining process. The highest input heat caused the escape of hydrogen and chloride from the structure of (PVC), the occurrence of the chemical degradation of polymer compounds and the observation of clear burning of the polymer at the joining area, which caused a decomposition of PVC by a phenomenon called (de-hydro-chlorination). During the degradation of PVC, drop of the mechanical properties, cooler change and lowering in the chemical resistance are occurred [10]. On the other hand, the parameters of the friction joining process, which were used in joining the sample 1, were in the least condition levels: linear speed 80 mm / min, rotational speed 800 RPM and 0.1 mm tool depth; the smallest levels of parameters caused insufficient heat input to melt the polymer.

3.2. Design of experiment (DOE) results

The Minitab program was used to analyse the effect of the process parameters on the AA6061-PVC joints shear strength. Figure 6 illustrated the main effect plot for all holes. For the first three holes, the results indicated the joining parameters exhibited the same effect on the shear force. The rotating speed and plunging depth of the tool exhibited a small effect on the shear strength of the joint. Increasing the hole numbers and diameter decreased the joint strength. The other parameters exhibited an alternative effect on the joints shear strength. The analysis of the main shear force plot at hole 4 is shown in figure (6d). It was observed that when the tool diameter and hole number increased lead to decrease the joint strength. Also, when the tool depth and rotating speed increased resulted in increasing the joint strength. Figure (6e) displays the main shear force plot at hole 5, in which, the increasing in hole diameter increased the joint strength.

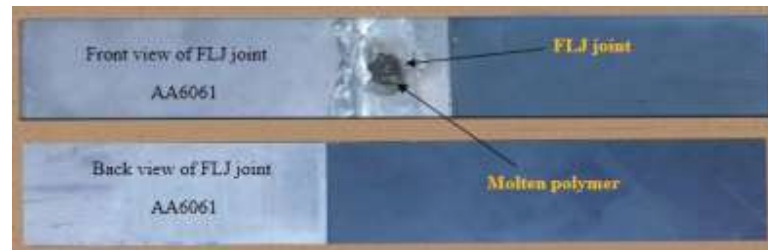


Figure 4. Typical joint of AA6061-T6-PVC

Table 4 . Shear force values for all holes of AA6061 with PVC joints.

Sample NO.	Shear Force (N) mix.	Shear Force (N)				
		Hole 1 Friction Start	Hole 2	Hole 3	Hole 4	Hole 5 Friction End
1	960	514	640	790	960	
2	1850	1056	1376	1850	1828	
3	1568	992	1504	1568	1516	
4	928	576	736	928	832	640
5	664	380	472	664	504	308
6	854	512	768	854	761	576
7	1632	1312	1632	1472		
8	1833	1448	1833	1580		
9	1825	1446	1825	1568		

The Pareto chart gives an indication of the degree of the effective factors of friction stir joining parameters on the joint shear force of the produced joints, as shown in Figure 7.

In general, the hole number exhibited the highest effective factor on the shear force compared with the other parameters. The tool depth was the lowest effective process parameter on the shear force of the joint at hole 1, 2, 3, and 4. For five holes, the hole diameter had the highest effective factor on the shear strength but the linear speed exhibited the lowest effect on the joint strength.

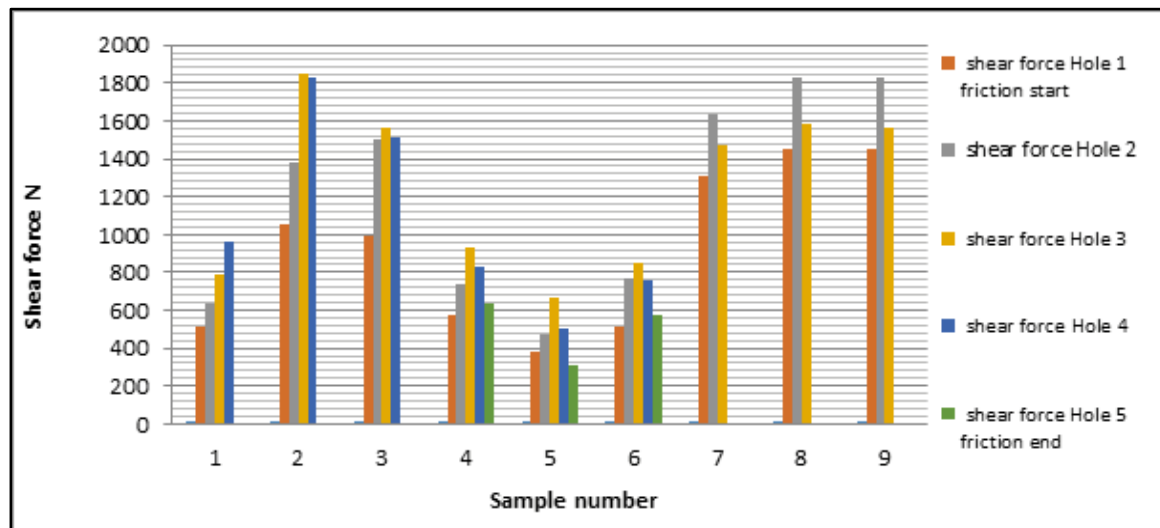


Figure 5. Variation of shear force with the sample number of AA6061 with PVC joints

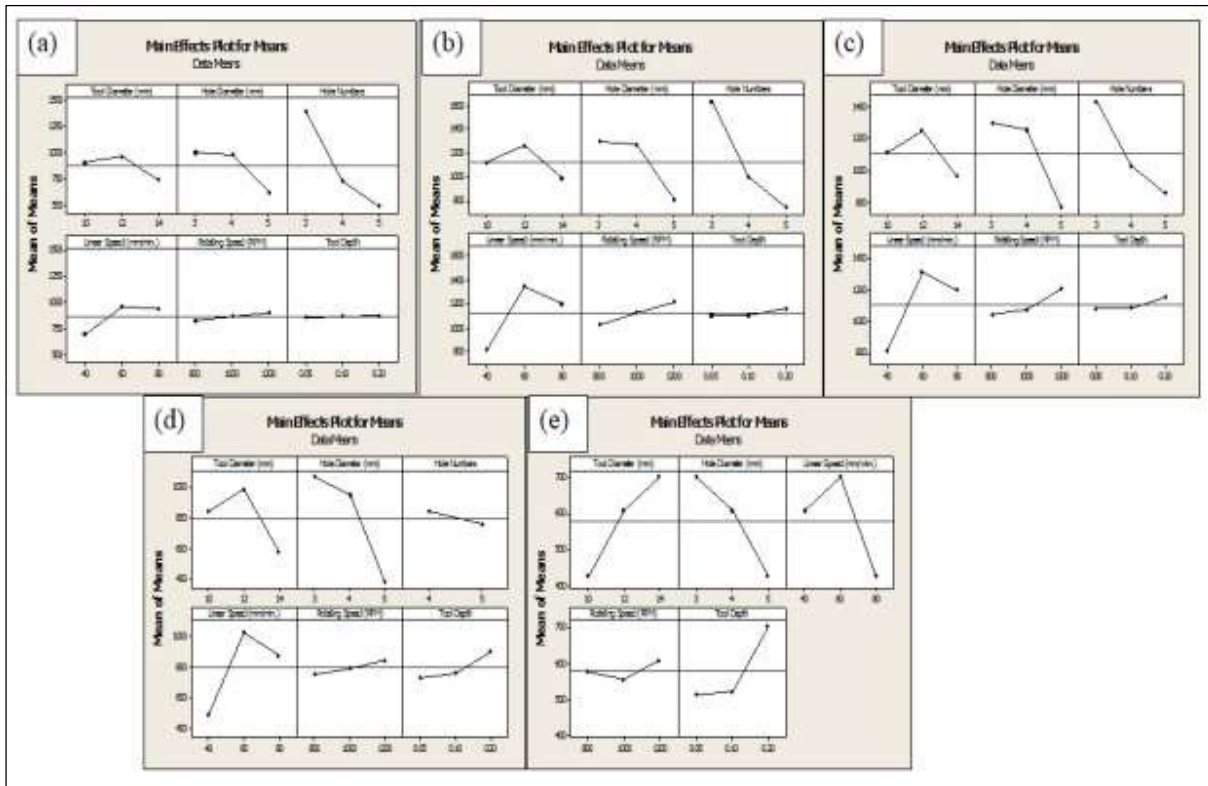


Figure 6. Main effects plot of the AA6061- PVC for (a) hole 1, (b) hole 2, (c) hole3, (d) hole 4, (e) hole 5.

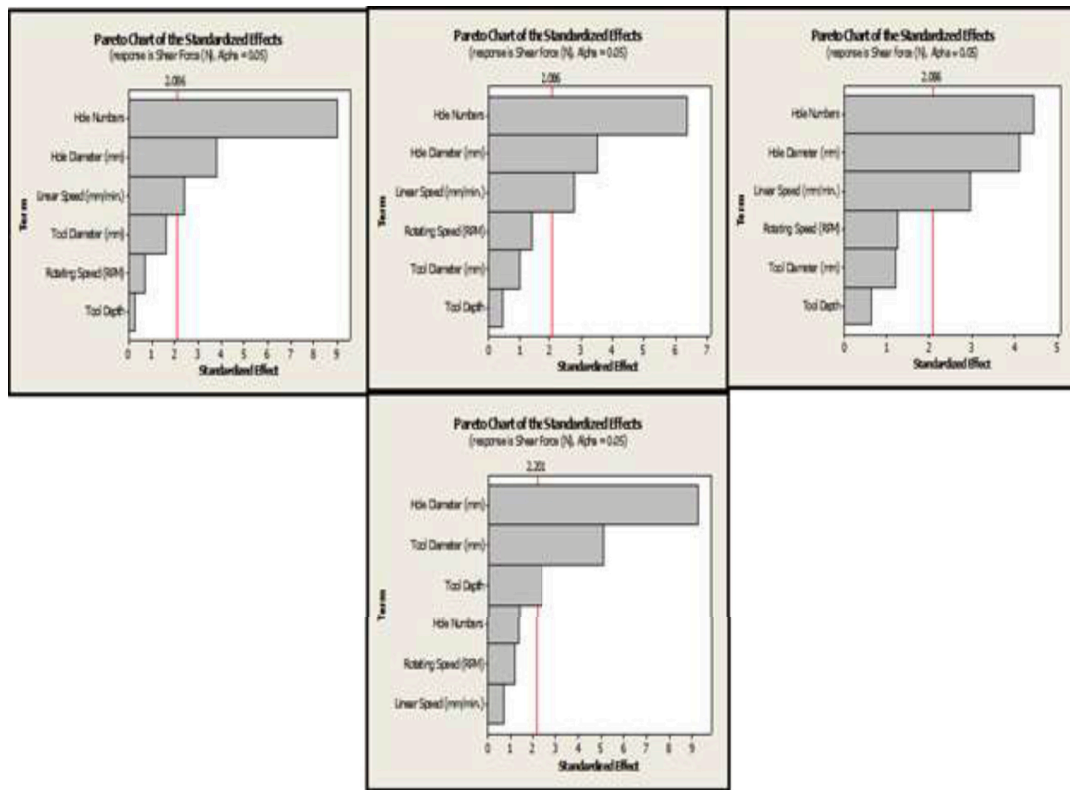


Figure 7. Pareto chart of shear force for the AA6061-T6- PVC for a) hole1,b) hole 2, c) hole 3, d) hole 4.

3.3. Heat distribution inspection of FLJ

Metals and polymers are completely different in many conditions such as physical, mechanical properties, structures, melting point. The melting points of AA6061, and PVC are 660, and (175–200) °C, respectively [11]. The joining mechanism between the AA6061 and polymer sheets (in this work) depends on the generating of adequate heat to molten the polymer and penetrating it throughout the aluminium specimen hole with the aid of the applied pressure. The source of the heat is generating by the friction process between the rotating tool and aluminium work piece [12].

The temperature distribution inspection was carried out on three samples of the friction lap joining process by using the reflected infrared ray; the samples were chosen with optimum shear force, medium shear force and low shear force sample.

Figure 8 shows the temperature profile at the AA6061-PVC joints during the frictional process. Low temperature degree was recorded in the sample 1 because of the parameters in this case are in low condition (low depth of the tool, low rotating speed and high linear speed). This case caused the low input heat in the joint zone where consequence not enough heat to melt the polymer and which produced a low joint. In the sample 2, the temperature was recorded within and below the melting point of polymer. This sample exhibited the best condition of the friction parameters and produced sufficient heat input with optimum joint quality between the aluminium alloy and polymer, which made the better joint. The temperature of the sample 5 are in the high condition, which cause the high input heat and led to increase the temperature over the melting point of the polymer with progressing the process. Consequently, the

higher temperature value caused the degradation temperature (the decomposition temperature). At very high temperatures, the covalent joins between the atoms in a linear sequence may be shattered and the polymer may burn or char. As a result, the sample 5 exhibited a small amount of the shear strength.

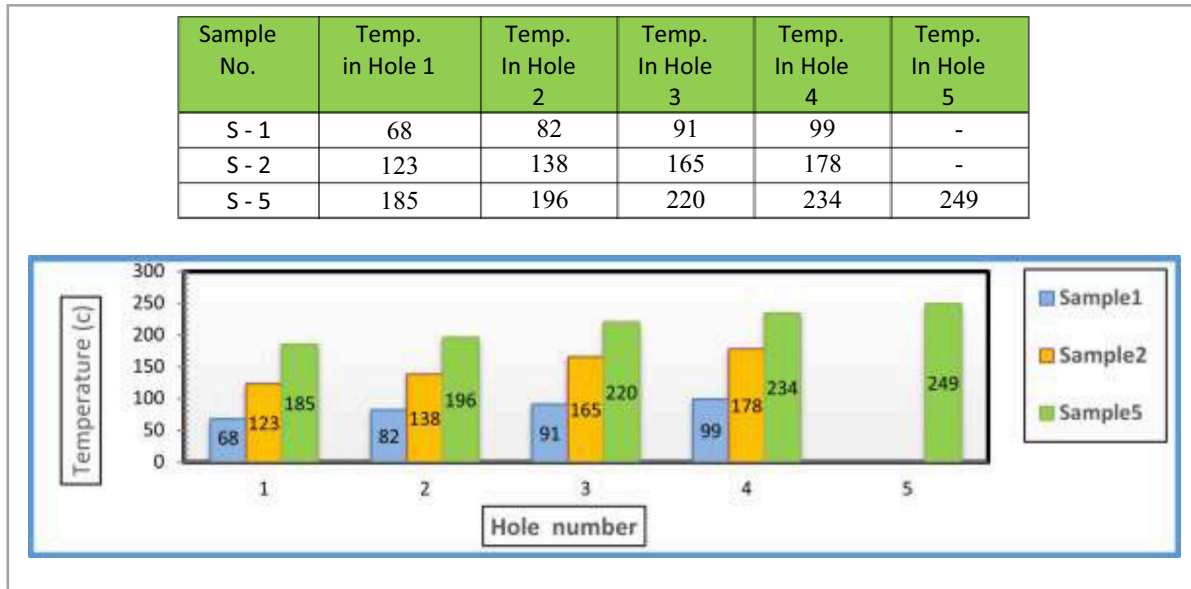


Figure 8. Temperature distributions along the joined line of A6061-T6 to PVC for three samples.

3.4. Microstructure examination

The cross-section of the joined sample of AA6061 with PVC was investigated by a microscope, which provided with a digital camera. The optimum joining condition sample was prepared for the micro inspections. The microstructure of the joint inside the hole of the aluminium specimen and the joint interface line between the two materials were clearly observed in figure 9. The fragments were distributed in different sizes from aluminium slag and entrapped in the re-solidified layer of the polymer at the joint cross-section.

The interface line between the two polymers indicated to the mechanical interlocking between the aluminium and polymer. The molten polymer in the area that adjacent to the interface line is melted during the friction lap joining process. The molten polymer transfers through the holes and mixed with the aluminium fragments. The re-solidified polymer mixed with aluminium fragments. As a result, aluminium sheet and polymer bonded together during the process by means of the mechanical interlocking [13] and chemical bond and metallic bond [14]. Defects such as small voids were detected at the boundary interfaces between the two materials. Moreover, the re-solidified polymer of joint type AA6061 with PVC exhibited voids at the surface of the re-solidified polymer.

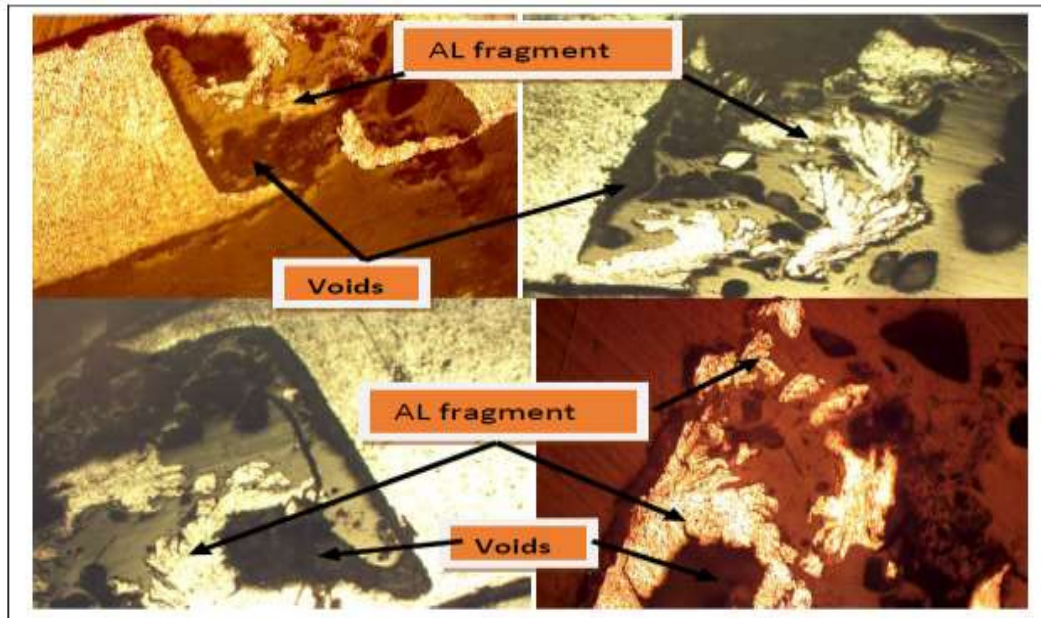


Figure 9. Microstructure of the joined zone in hole and the interface for AA6061 with PVC.

3.5. Surface appearance of the fracture surfaces



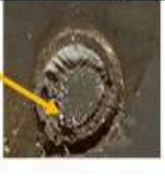






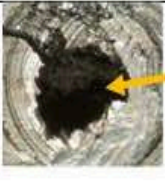
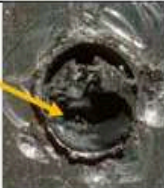

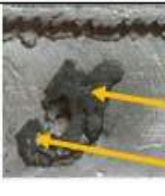

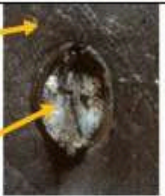
Table 5, illustrates the inner and outer surface appearance of the tested joints of AA6061 to PVC specimens in the region of the fractional processing. A samples failed by shear stress test at the lap joint region[15] without any dislocation due to that the molten PVC in the cap of the aluminium specimen prevented the polymer dislocation from the aluminium specimen through the shear force test. The molten polymer (PVC) mixed with aluminium fragments during the frictional process [3].

3.6. Energy dispersive spectroscopy (EDS) and Elemental mapping (EM) analysis

The EDS analysis provides useful information about the chemical composition of the aluminium alloy and polymer at the joint area. The changes in chemical composite at the joint zone affect on the adhesion joint properties between the aluminium and polymer, and furthermore the mechanical performance of the joints. The EDS line analysis was carried out to locate the distribution of elements across the friction lap joining of aluminium to polymer joints, as shown in figure 10.

The EDS analysis indicated that the joint zone consists of the main element of (Al, Cl, Si, O and a small amount of Mg. The EDS spectrum line was taken from Al side passing through the joining area and arrived in the polymer side. The composition was mainly consisted of aluminium, silicon and a small amount of the (oxygen and magnesium). When the spectrum moved through the joint zone inside the hole, the composition appears to be contained the (Al) element with a high amount of (Cl), (C) and (Si) due to chemical join. The element analysis indicated to the successful joining between Al to PVC with the aid of chemical joining by the Van der Waals join and the mechanical interlocking between the two materials.

Table 5. Fracture Surface appearance of the lap joints of AA6061- PVC

Sample NO.	Outer surface of AA6061	Inner surface of AA6061	Inner surface of PVC
2 Fully mixed	 C	 F	
1 Partially mixed	 C	 P	
5 Partially mixed	 C	 F D P	
8 Fully mixed	 C	 C F	
7 Fully mixed	 P C F	 D F	
F= Al fragment		P =Pure polymer	C = Composite materials
			D = Degradation

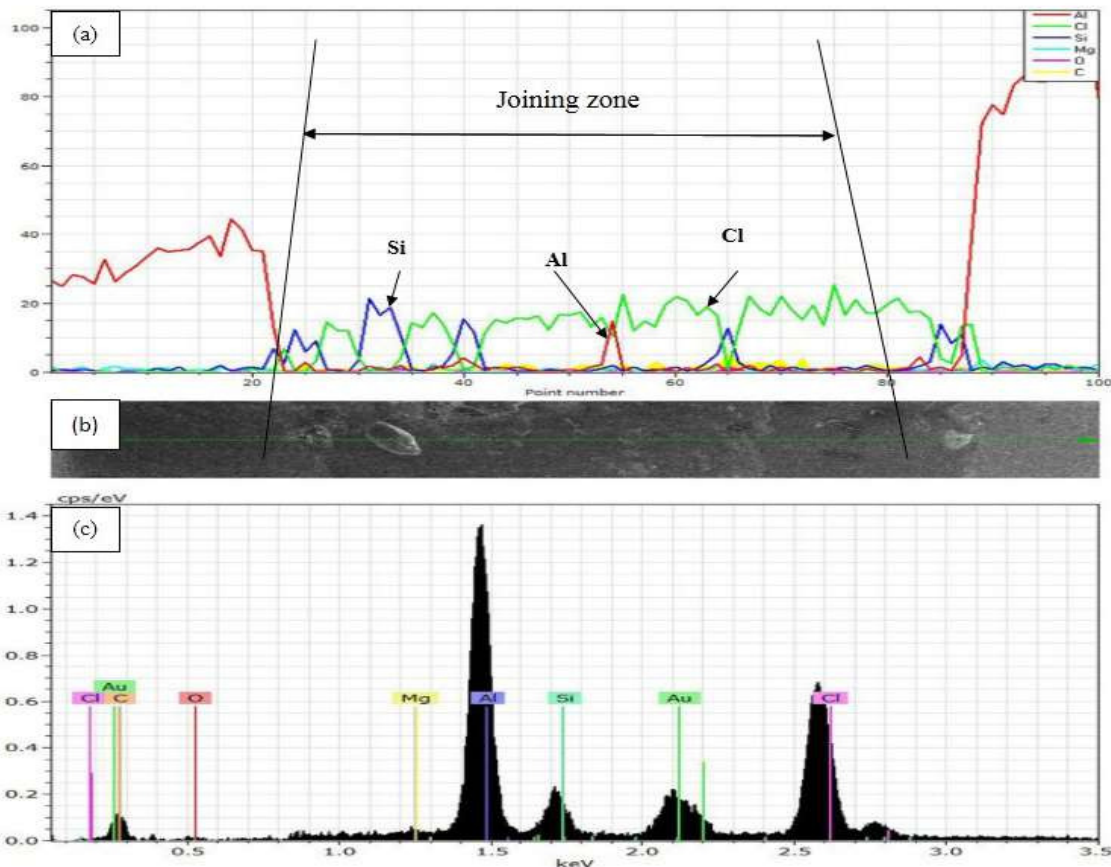


Figure 10. EDS line of the optimum condition for the sample: (a) elements behaviour (b) element analysis.

The Elemental mapping of the microstructures, elemental analysis and/or chemical characterization of a sample has been done by scanning electron microscopy and energy dispersive X-ray spectrometry (SEM-EDS) devices. The test was carried out for Al - PVC joint sample at the optimum shear force to study the detailed map of elements distribution at the joined zone and the interface between the aluminium and polymer to give an impression about the joining structure.

Figure 11 display the inspection applied at joint zone (the hole area). A high amount of the aluminium element distributed at the aluminium alloy side and diffused in the joint zone which made the composite metal with other elements (Cl, C and Si) to produce the joining in this region between the two materials. The silicon and carbon elements diffused and distributed for all mapping data of these joint. A high amount of the chloride distributed through at PVC side.

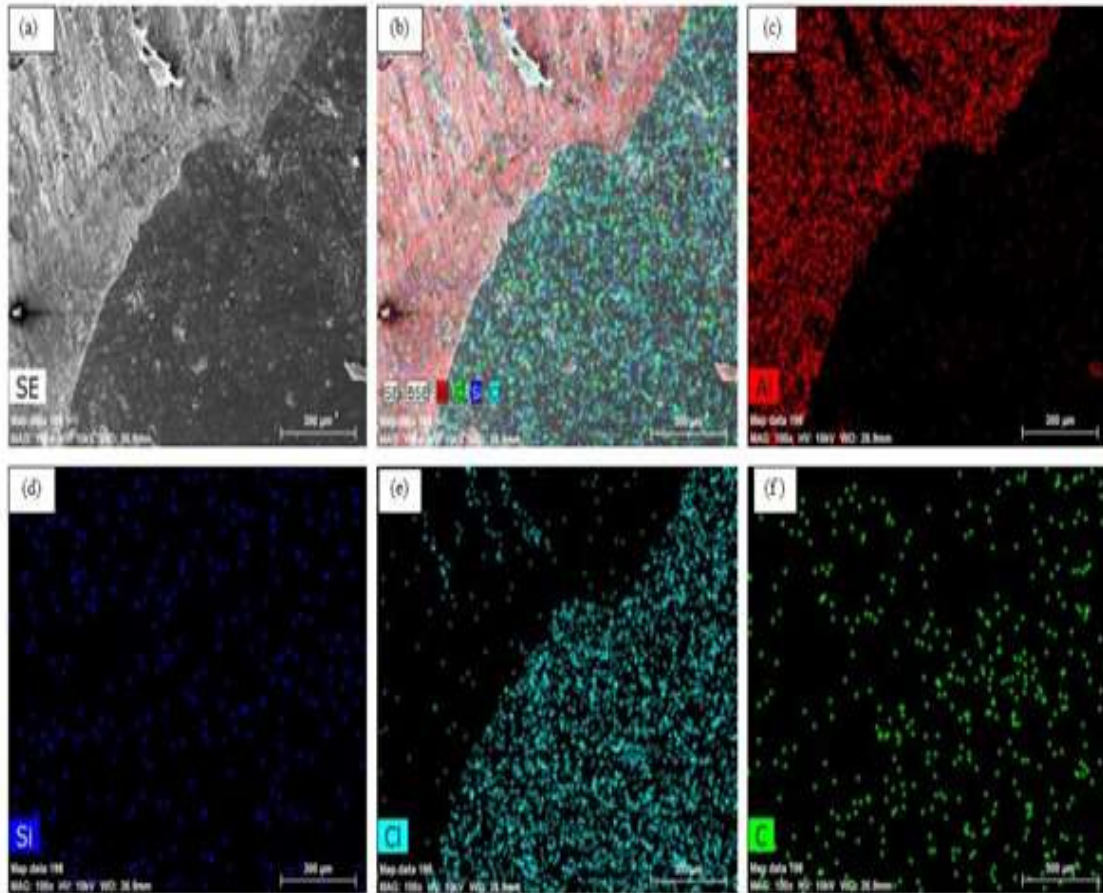


Figure 11. SEM. Analysis of AA6061-PVC joint a) SEM. Map data of joint zone, b) SEM. Data Analysis of joint zone, c) SEM. data for AL, d) SEM. data for Si, e) SEM. data for Cl, f) SEM. data for C

3.7. Scanning electron microscope (SEM) and optical microscope (OM)

The SEM examination was achieved in the joints for a case of the optimum conditions. The images indicated that the joining zone of the holes exhibited a clear variation in the size of AL- fragments of (11-30 μm, ...etc.) which diffused internally in the re-solidified polymer. A mechanical and chemical joining occurred between the elements of aluminium alloy and polymer, as shown in figure 10.

The microstructure indicated that the mechanical interlocking occurred at the joint by filling the cavities of the AA6061 alloy layer with the molten polymer. As a result, this phenomenon widens the participation of Vander Waals as a joining [12]. It was detected that the joint was tightly joined without the gap between two materials and completely mixed by the inter-diffusion process of melted plastic due to the generated frictional heat that resulted from the rotational tool [14]. The microstructural features of the (FLJ) joint contain entrapped aluminium fragments in a compacted polymer matrix [3]. The joint exhibited the voids inside the hole and underneath the interface.

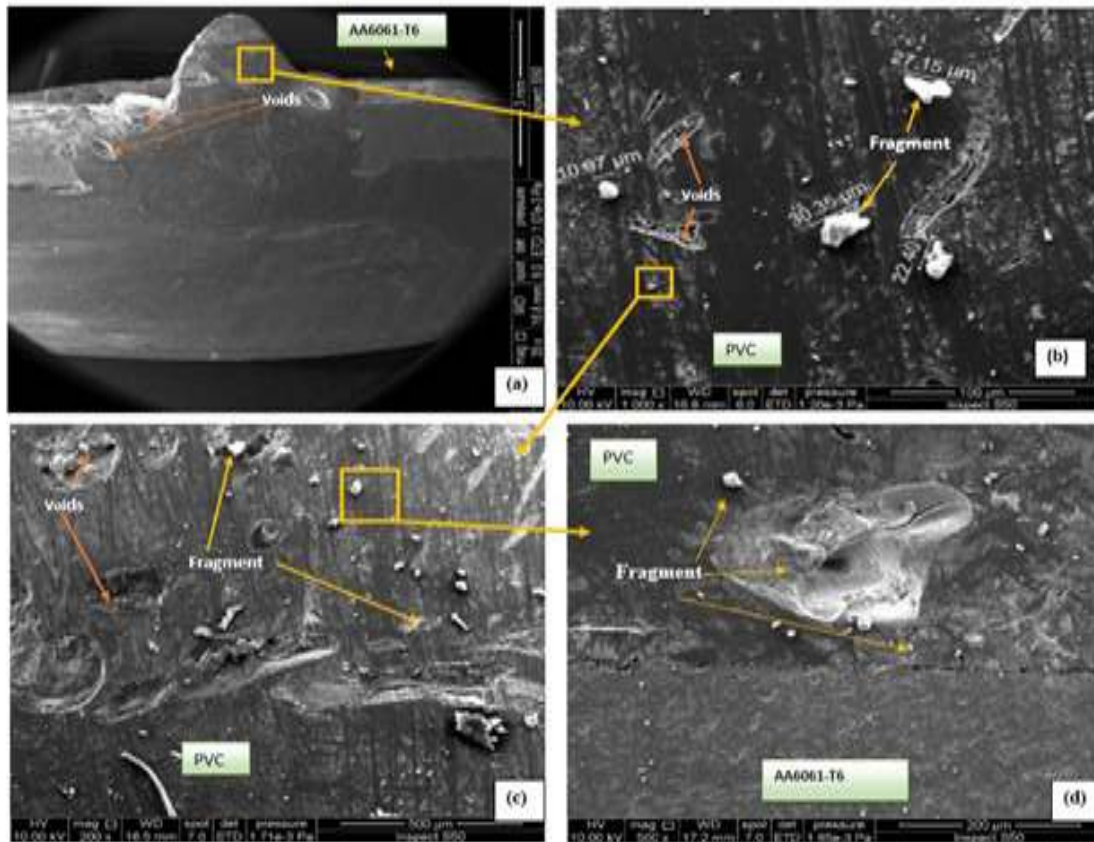


Figure 12 SEM images at the optimum conditions for AL – PVC joint at: (a) Al-PVC joint zone,(b) as shown in a(c)as shown in b (d) as shown in c.

4. Conclusions

Lap joints of the PVC to AA6061 were achieved using the frictional process with various processing parameters. The following conclusions can be drawn:

1. The PVC joined successfully with the aluminium alloy with the aid of the entrapped the aluminium fragments through the re-solidified polymer.
2. The joining mechanism between the polymer and the aluminium occurred by a mechanical interlocking between the two materials.
3. The joints properties depended on the joined area dimensions, frictional process parameters and the amount of aluminium fragments in the re-solidified polymer.
4. Increasing the hole numbers and diameter in the aluminium specimen decreased the joint strength for all the joined specimens.
5. The Increase in the rotating speed and plunging depth of the rotating tool increased the joint strength, while the linear speed and diameters of the tool exhibited a fluctuating effect on the joint strength.
6. The hole number and diameter had the highest effect on the joint strength.
7. The optimal shear force was recorded for the AA6061 with PVC joint with a range of 1810- 1850N.
8. The SEM and EDS analysis showed that a composite metals bond formed at the hole and interface joint consisting of the aluminium fragment entrapped through a re-solidified polymer.
9. The process temperature is the highest effected on the AA6061-T6 with PVC joint strength.

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