IOP Conference Series: Materials Science and Engineering

PAPER • OPEN ACCESS

Friction Spot Joining (FSpJ) process of Aluminium AA6061-T6/Poly Vinly Chloride (PVC)

To cite this article: Faeq Yaseen Sadkhan *et al* 2021 *IOP Conf. Ser.: Mater. Sci. Eng.* **1105** 012043

Friction Spot Joining (FSpJ) process of Aluminium AA6061-T6/Poly Vinly Chloride (PVC)

Faeq Yaseen Sadkhan[1.a], Sabah Khammass Hussain[1.b], Abdulwahab Hassan Khuder[1.c]

[1] Engineering Technical College, Middle Technical University, Baghdad, Iraq.
E-mail: [a] Eng.faeq75@yahoo.com [b] sabah.kh1974@yahoo.com, [c] akhuder4@gmail.com

Abstract. The goal of this research is to use a Friction Spot Joining (FSpJ) is a new technique which used for joining hybrid structures of metal-polymer composite. The FSpJ was proposed to join sheets of aluminum alloy of type AA6061-T6 and polymer of type polyvinyl chloride (PVC). The aluminum alloys sheets were of 3mm thickness, while the polymer sheets were of 5mm thickness. All sheets were manufactured with dimensions of 25*100 mm^2. The aluminum sheets were drilled with two holes: the first of 8mm diameter with 1mm depth, the second hole was of the same pervious hole center with a penetrating hole diameter of d mm (2,4 and 6). the aluminum holes were made at a the center of the lap joint area. The process parameters included the rotating speed of the tool of 710, 900, 1120, 1400 and 1800 RPM, plunging depth of the tool of 0.1, 0.2, 0.3, 0.4 and 0.5 mm and pre-heating time of 5, 10, 15, 20 and 25 sec. The results indicated that all the specimens were joined successfully. The tested sample indicated that the failure of FSpJ joints occurred at two locations; the first at polymer side and the second was occurred by shearing the lap joint of specimens. The first type of failure indicated that the shear strength of the joined samples exceeded the shear strength of the polymer with a shear strength joint efficiency of more than 100%. The specimens that failed by shearing the polymer at the lap joint region were failed without dislocation the molten polymer from the aluminum hole cup. The shear force of the AL-PVC joints ranged from (704 - 1664N). The hole diameter exhibited the highest effect on the joint shear force followed by the plunging depth, rotating speed and pre-heating time of the rotating tool. The macrostructure examination and SEM tests indicate that a macro mechanical interlocking formed between the metal and filled hole which attributed to the main joining mechanism at the common surface.
Keywords. Friction Spot Joining, Aluminium alloy, Polymer (PVC), Mechanical properties, Microstructure and Fracture.

1. Introduction

Material science has a long history; it has a profound impact on the evolution of human civilization. From stone age to the modern age, there has been a significant development in the material science field [1]. There is a continuous introduction of various new materials now to suffice the material requirements of the rapidly developing automobile, aerospace, and other industries. In the 21st century, the key to a successful product in many industries is to have a good customer value and minimum environmental impact [2]. One of the approaches used by industries to reduce the environmental impact is by reducing the weight of the product. Weight reduction can be achieved by the use of a material having a low material density such as lightweight alloys and polymers. For example, in aerospace industries weight reduction can improve fuel consumption, reduce maintenance frequencies and increase range. The use of advanced material or combination of several dissimilar materials can enhance the overall mechanical properties, which have given rise to the scientific material age with material of superior performance characteristics [1, 3]. Lightweight metal and the polymer have excellent mechanical properties for structural applications. Some polymeric materials are stronger than the metals, with high mechanical chemical and corrosion performance properties. Although the separately use of lightweight material and polymer, extensively, in various applications, the combination of both materials is considered an area to be explored to further optimize weight and enhance the performance of the overall structure [4]. The use of multi-material structures is extensive in various transport industries such as automotive, aerospace and shipbuilding [3, 5]. With the evolution of multi-material structure, the need for joining dissimilar materials together is a vast area to explore. Although several methods are available to join, the dissimilar metal but the process for joining the metal to the polymer is very few. Building a complex engineering component by joining the various dissimilar materials has developed with various new joining methods in the field of materials joining [5, 6]. Due to the possibility of exploiting the peculiarities of each material, the area of the dissimilar material structure has a high potential. For this purpose, suitable joining methods are necessary to join those dissimilar materials and integrate them into engineering structures.

In the present study, an aluminum alloy of type AA6061-T6 was joined with polymer of type Poly vinyl chloride (PVC) by frictional spot lap joining (FSpJ) technique. The joining has been done with a wide range of rotational speed, different hole diameter in the aluminum specimen, pre-heating time and plunging depth of the tool. The experimental plan was build using the design of experiment method to identify the effect of the parameters on the joint quality and evaluates the effect of the significant parameters.

The mechanical properties of the joint were investigated by the shear tensile test. The macrostructure, microstructure, scanning electron microscopy (SEM) and energy dispersive spectroscopy (EDS) of AA6061-T6/PVC joints were examined to analyse the joining mechanism at the interface line of the joints.

There are currently few joining processes available to join aluminium alloys to polymer-based materials. With the limits that exist, with the joining processes currently available, the research presented here aims to introducing the development and evaluation of a new efficient method for joining these types of dissimilar materials. Compared to existing alternatives, this new approach has distinct benefits and comes at a time when the perceived need and market is increasing for these metal-to-polymer joints.

2. Experimental procedure

2.1. *Materials and specimens preparations*

Two types of materials were used in the joint process: AA6061-T6 and PVC, having a thickness of 3 and 5 mm, respectively. The chemical composition for Al is listed in table 1 and the mechanical and physical properties for Al and PVC. The specimens were fabricated according to the standard dimension of the lap joint [ASTM B209], such that the width, length and thickness of each specimens remained constant for all samples. The drilled holes were manufactured in the AA6061-T6 specimens to prevent the dislocation of the melted PVC from the aluminum specimen in the tensile test. The dimensions of the external hole (d2=8) remained constant, The outer diameter works to allow the molten polymer to penetrate into the inner diameter and fill it in order for the interlock area is formed in the bonding area in addition to allowing the exit of gases and excess molten polymer during the joining process, which increase the joint strength. except the lower holes diameter (d1). Three values of d1 were used: 2, 4 and 6mm to study the effect of the diameter variation on the shear force of joint. Figure 1 represents the manufactured samples of the AA6061-T6 and PVC.

Polyvinyl chloride, is a thermoplastic polymer; and one of the most three widely used polymers in the world, with polyethylene and polypropylene. the general chemical formula of the PVC is $C2H3Cl$ and the density is about 1.38 g/cm^3. The mechanical Property of PVC which has a chemical and physical structure that makes it broadly unique in the polymer world [7, 8]**.**

Table 1. Chemical composition and material property of AA6061-T6 and PVC

Element wt%	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Balance
Standard ASTM(B209)	0.4-0.8	0.7	0.15-0.4	0.15	0.8-1.2	0.04-0.35	0.25	0.15	Balanced
Measured	<0.8	0.510	0.233	0.127	0.959	0.211	0.056	0.062	Balanced
Material Property			σu (MPa)		σy (MPa)		% Elongation		
Nominal			290		240		12		
Measured			328		264		13.5		
			Tensile Strength Mpa		Yield Strength Mpa		Elongation %		
PVC			53		40		141		

2.2. Model Description

Each specimen was prepared with dimensions of 25 × 100 mm² according to the Standard specification of the American Welding Society (AWS C1.1 M/C1.1:2012) of a lap joint area of 25 × 25 mm² aluminum specimen is drilled with holes at the center of lap joint and placed over the polymer specimen as shown in figure 1.The rotating tool is moved down and penetrated into the aluminum specimen with a specific height during the process. The cross-section dimensions of the lap joint are shown in figure 1c. Where, t1 and t2 represent the thickness of the aluminum and polymer specimens, respectively. The aluminum specimen was machined two holes of d1 and d2, respectively. The lower hole was machined with a height of h1, while the upper hole with a height of h2.

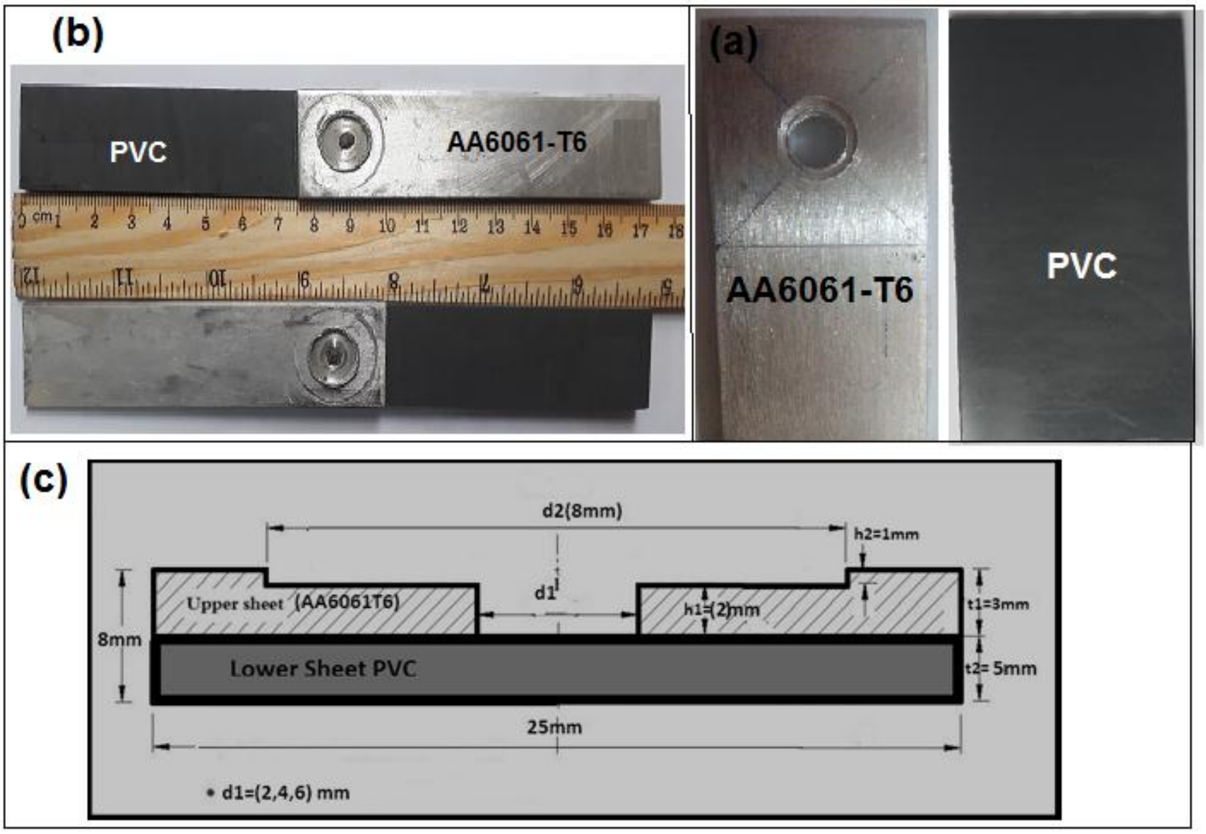

Figure 1. The manufactured samples of the AA6061-T6 and PVC. (a) AA6061-T6 with two holes and PVC, (b) schematic of lap joint, (c) cross-section dimension of the lap joint with holes.

2.3. The Joining Process

The joining process was achieved by two steps: Firstly in melting the polymer at the region nearby the hole of the aluminum specimen. Then secondly, penetrating the molten polymer through the hole under the applied pressure of a pin-less tool of 12mm by using the friction spot joining with the aid of a vertical milling machine, as shown in figure 2. The vertical feed of the machine provides the necessary pressure by penetrating the rotating tool through the aluminium specimen with a specific plunging depth. A cylindrical high speed steel pin-less, having a shoulder diameter of 12 mm. Joining process was carried out with an overlap configuration in such manner that aluminum sheet was positioned on the top of the PVC sheet. Initially, the rotating tool was moved downward until it touches the aluminium surface. In this step, the rotational friction between the upper surface of the aluminum specimen and the lower surface of the rotating tool pre-heat the aluminium metal. The generated temperature melts the PVC material, which moves upward toward the aluminum hole under the applied load of the rotating tool, As illustrated in figure 3. The preheating time (5,10,15,20,25) sec) and the shoulder penetration depth (0.1,0.2, 0.3, 0.4, 0.5) mm) were based on the outcome of the preliminary experiment while the tool rotational speed was varied as(710, 900,1120,1400,1800) rpm .

Figure 2. Vertical Milling Machine.

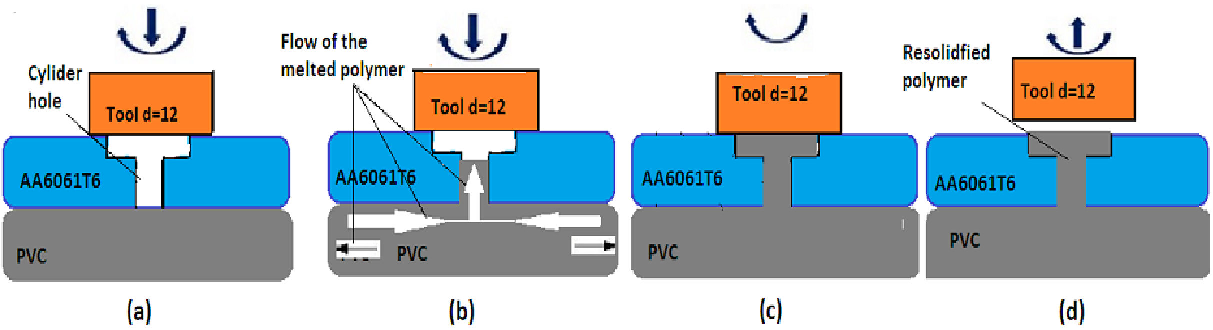

Figure 3. Graphical illustration of the steps for the joining process: a) Frictional heating and axial pressure, b) In-filling of the cylinder hole by the molten polymer, c) Filled hole by molten polymer and d) Tool retraction.

2.4. Design of the experiments

The work plans to study the effect of joining parameters on the joint strength. Four process parameters were used; holes diameters, tool rotational speed, pre-heating time and plunging depth, each one has five levels. A Taguchi method was used to analysis the effect of the joining parameters on the joint quality using the design of experiments method with the aid of the Minitab software. The tool diameter was kept constant during the process (shoulder diameter = 12mm). The design of the experimental parameters are illustrated in Table 2. Fifteen samples of the dissimilar materials (AA 6061T6 and PVC) were joined together using FSpJ processing. In figure 4. represents a samples of the joined specimen.

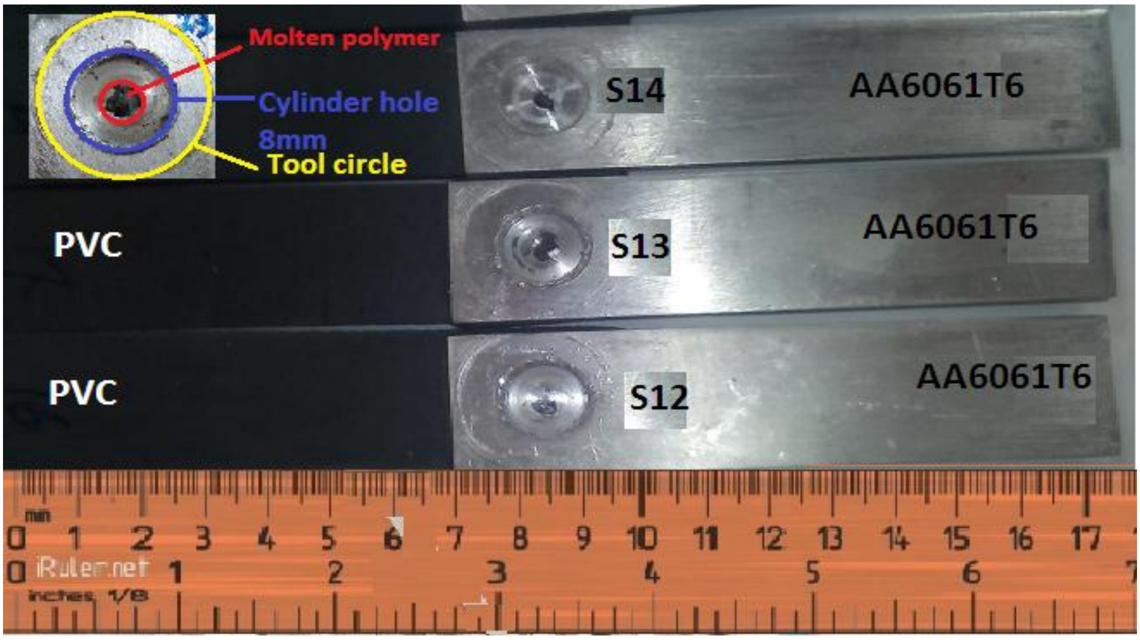

Figure 4. Sample of the joined specimens for AA6061T6- PVC by friction spot process.

3. Result and discussion

3.1 *Tensile shear test of the joints*

The joined specimens have been tested by a tensile shear test for joint type AA6061T6-PVC in order to determine the mechanical properties of this joint. The influence of the joining parameters on the shear force of the joint was analyse. The AA6061-T6 fragments with the melted polymer created a composite material(CM) through the polymer matrix and produces joint region by mechanical interlocking and/or chemical joining [9].

The mechanical properties of a composite material depend on the volume fraction of the particles (fragments) of AA6061T6 and the mechanical properties of polymer-matrix and particles.

The shear forces results of the joints type AA6061T6 – PVC were listed in table 2. The tested samples were based upon Taguchi plan in the experimental work. different values in the shear forces behaviour were observed in those joints against the selected parameters. The shear force values ranged between a minimum shear force of 704N in samples 1 and 4 to maximum shear force of 1664N in sample 14 and 15. The reason for this difference in joint properties is due to the chemical composition of the PVC which contains the hydrogen and chlorine (HCL) in structure, and their significant influence with temperatures. When the temperature rises to crystalline temperature, which is lower than the melting point of (PVC), because a decomposition of PVC by phenomenon (de-hydro-chlorination). During the degradation of PVC, a drop of the mechanical properties, cooler change and declines in the chemical resistance are occurred [10].

Table 2. Design of the experiments parameters using Taguchi approach and shear force of the joints AA6061T6-PVC

Sample No.	Hole Diameter d1 (mm)	Rotation Speed N(rpm)	Plunging Depth Y(mm)	Preheating Time T(sec)	Shear Strength test (N)
1	2	710	0.1	5	704
2	2	900	0.2	10	768
3	2	1120	0.3	15	896
4	2	1400	0.4	20	704
5	2	1800	0.5	25	768
6	4	710	0.3	25	1152
7	4	900	0.4	5	1152
8	4	1120	0.5	10	1216
9	4	1400	0.1	15	1024
10	4	1800	0.2	20	1280
11	6	710	0.5	20	1536
12	6	900	0.1	25	1216
13	6	1120	0.2	5	1024
14	6	1400	0.3	10	1664
15	6	1800	0.4	15	1664

The diversity of the parameters used in the frictional joining process gives the convergent results in using the lower holes diameters (d1) of (2,4 and 6 mm). It was recorded that the lower hole diameter (d1) of (6mm) was the best diameter that used to join this type of materials. Hence, the joined specimens by those holes have shear force values ranged from (1024 to 1664 N). Figure 5. represents the experimental shear force data for the 15 samples of the dissimilar joints type AA6061-T6/ PVC with different joining parameters. The results were recorded at the maximum shear force value in the tensile test, which represented the shear force at the final fracture of the joined specimens .
To compare the results of the average shear force of each diameter (d_1), the average of shear forces of the joints exhibited the minimum values at the sample of the minimum d_1=2mm (S1, S2, S3, S4 and S5), which are varied between 704 to 896N. The average values of the joint shear forces increased gradually as the d_1 increased to d_1=6mm. At d_1=4mm, the range of shear force was between 1024 to 1280N. At d_1=6mm, the range of shear force was between 1024 to 1664N. As a results, increasing the hole diameter of the aluminium specimen increased the shear force of the joints. The hole diameter exhibited the highest effect on the joint strength compared with the other parameters in the Joining of AA6061 to polyvinyl chloride via hot extrusion process [11]. This can be consoled to the fact that the increasing in the hole diameter allow to contain a maximum amount of the molten polymer and/or aluminium fragments in the aluminium hole. The higher amount of the composite material (molten polymer and aluminium fragments) in the aluminium hole increase the joint shear force.

It was observed that the other parameters (pre-heating time, rotating speed and plunging depth of the tool) exhibited an alternating effect on the joint shear of the sample. The highest rotating speed(1800RPM) recorded the maximum shear force values at the sample of d_1=4 and 6mm. The maximum shear force at the hole diameters of d_1=2 and 6mm Was recorded at a pre-heating time of 15 seconds. The minimum shear force at the hole diameters of d_1=2 and 6mm was recorded at a pre-heating time of 5 sec. Pareto chart illustrates the standardised effect of each process parameters on the shear force of the joint as shown in figures 6,7 and 8. It was observed that holes diameters have the highest effect on the shear force of joint as compared with the plunging depth and tool rotation speed. However, the pre-heating time showed minor effect. The highest effect of the interaction parameters was observed between the plunging depth and the tool rotation speed. As explained above, increasing the hole diameter of the aluminium specimen increases the shear force of the joints. As a results, the hole diameters of the aluminum specimen exhibited the highest effect on the shear force of the joints, and hence, the amount of the molten polymer and/or the aluminum fragments determined the shear force value of the joints. In addition, the plunging depth of the rotating tool played the second parameters that effect on the joint shear force. Increasing the plunging depth of the rotating tool increased the applied pressure on the lap joint of the sample, which increased the applied pressure on the PVC specimen. As a result, the amount of molten polymer increases as the applied pressure increase. Therefore, increasing the plunging depth of the rotating tool increased the amount of the molten polymer in the hole of the aluminum specimen, which increased the shear force of the joint. The rotating speed of the tool played the third order on the shear force. This parameter develops the required heat to melt the polymer. The pre-heating time exhibited the minimum effect on the joint shear force. This indicated that that the developed heat during the joining process was higher than those from the initial step of the pre-heating time.

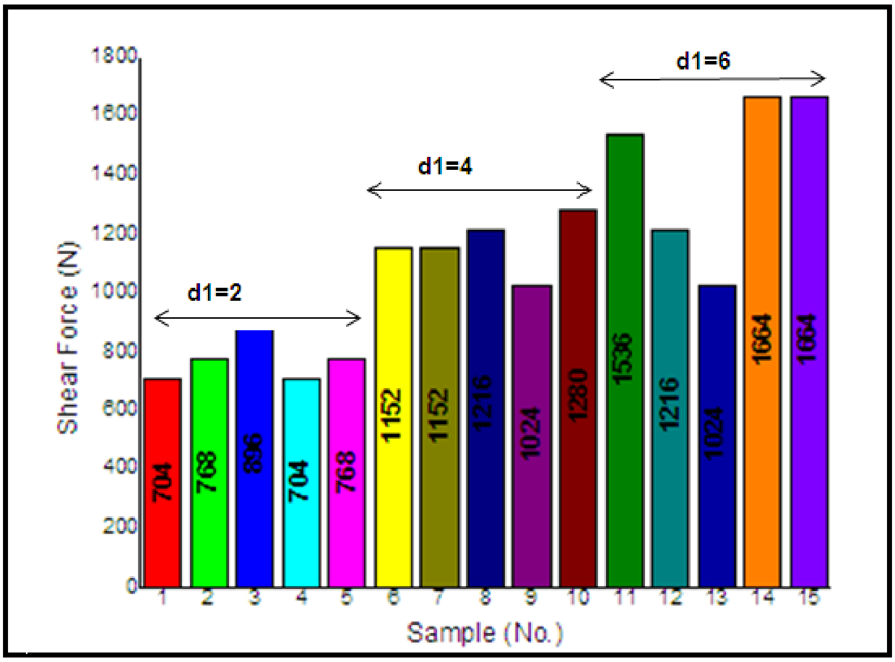

Figure 5. Variation of the experimental shear forces with process parameters

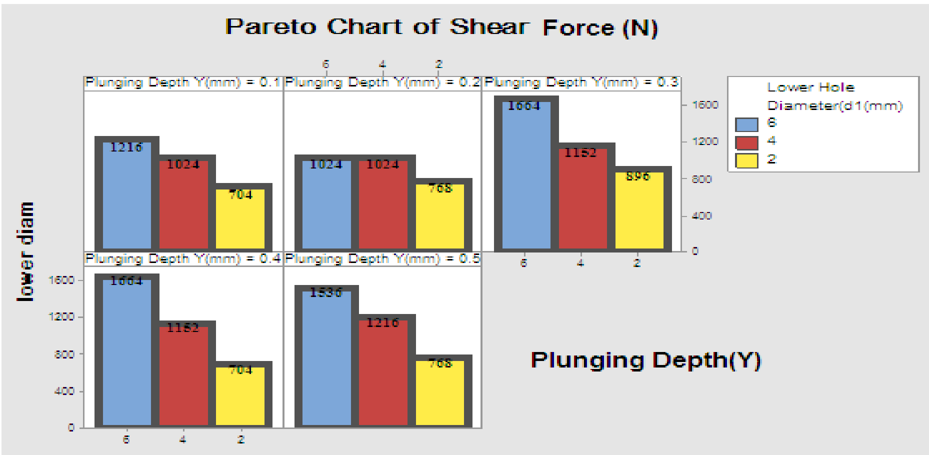

Figure 6. Pareto chart of the shear force- joining parameters (plunging depth).

IOP Conf. Series: Materials Science and Engineering 1105 (2021) 012043 doi:10.1088/1757-899X/1105/1/012043

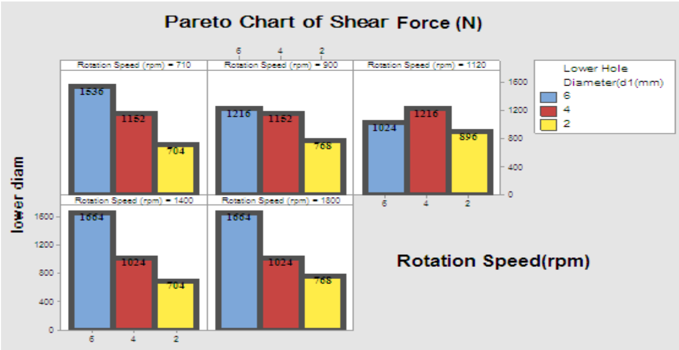

Figure 7. Pareto chart of the shear force- joining parameters (rotation speed).

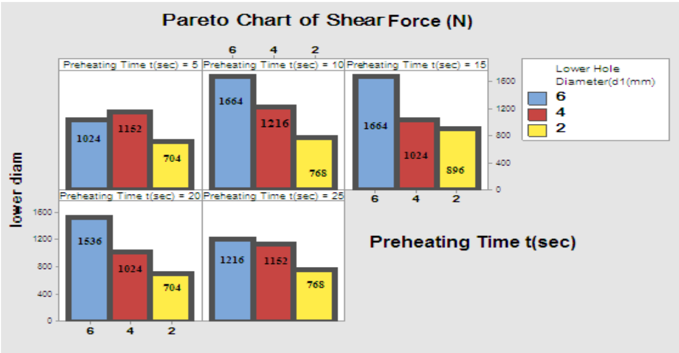

Figure 8. Pareto chart of the shear force- joining parameters (preheating time).

Figure 9 illustrates the effect of the result of the shear force of the FSpJ joints which were analysed by the design of experiments (DOE) method. The main effect plot showed an increase in shear force as the hole diameter (d1) increases until it reaches a diameter of 6mm. Increasing the rotating speed at 710 to 1800 RPM increased the shear force of the joints. All ranges of the plunging depth of the rotating tool except (0.1-0.2) increased the shear force of the joined samples approximately, increasing the pre-heating time decreased the joint shear force values.

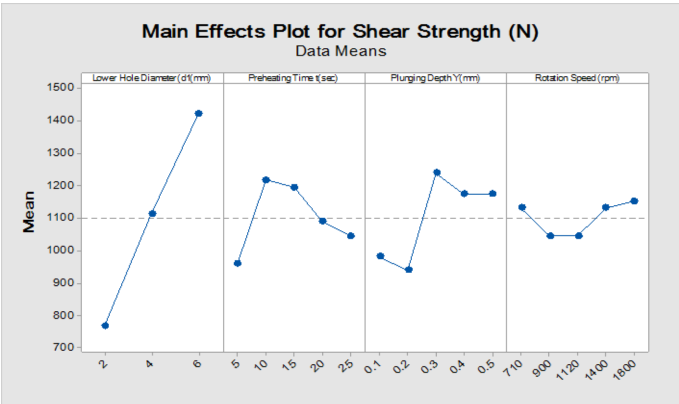

Figure 9. Main effects plot of shear force of the joints.

3.2. Surface appearance of the fractured surfaces:

figure10. illustrates the inner and outer surface appearance of the tested joints of AA6061T6-PVC at fracture region. The failure was shearing the composite material (PVC and aluminum fragments) at the cross-sectional area of the aluminium specimen hole, and this also happens for the remaining samples. The sheared samples were failed by shearing the molten polymer without dislocating the molten

polymer from the aluminium holes, as shown in the sheared region in the inner surface of the aluminium and PVC specimens. This has been done with the aid of the cup hole of the aluminium specimen, where the molten polymer reached this hole and prevented the dislocation of the polymer during the shearing test. The tested samples confirmed that the molten polymer filled the inner hole and reached the cup hole. Also, the formulated fragments during the friction spot process were mixed with the molten polymer [9] to form a composite material. Two forms of mixing were observed: fully and partially mixing of the polymer with the formulated fragments depending on the process parameters. The inner surfaces of the two specimens express a small deformation along compressed area due to the applied load of the rotating tool. The amount of the plastic deformation on the specimen area depends on the applied load of the rotating tool.

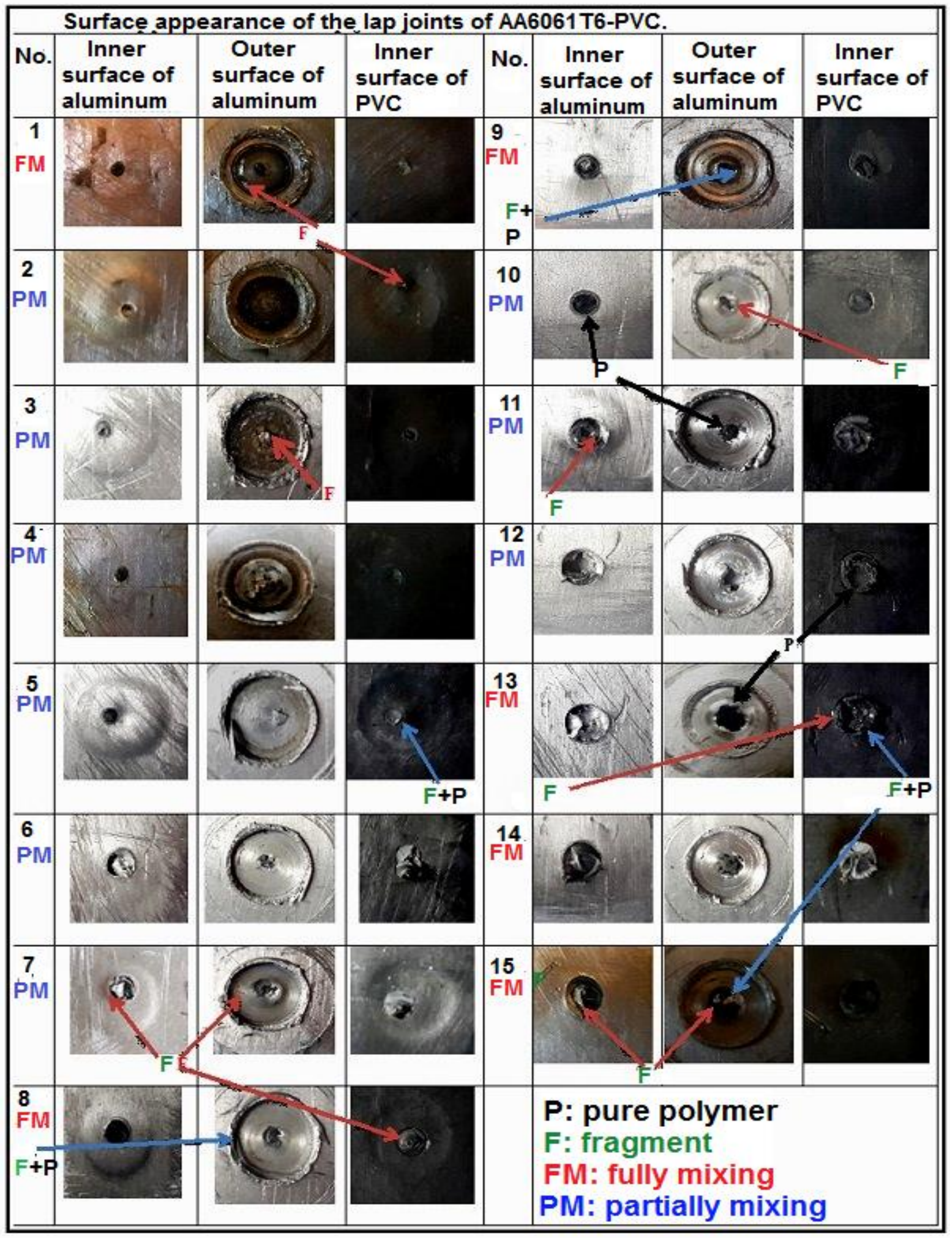

Figure 10. Surface appearance of the lap joints of AA6061T6-PVC.

3.3 *Visual inspection and macrostructure examination*

The visual inspection shown in figure 11 explains the molten polymer for the visual features of the joints Al-/PVC of the sample No.5.This joint was produced with a hole diameter of d1=2mm, rotating speed of 1800 rpm, pre-heating time of 25 sec and plunging depth of 0.5mm. An amount of burned PVC was observed around the edges of the lap region at the aluminum specimen. The higher input heat is progressed during the frictional process, which led to the degradation of the PVC material away from the lap region. The burned PVC occurred by successive elimination of hydrogen chloride (HCL), which is invited de-hydro-chlorination. During this phenomenon (degradation of PVC), a dropping in the mechanical properties and reduction in chemical resistance occurred [12].

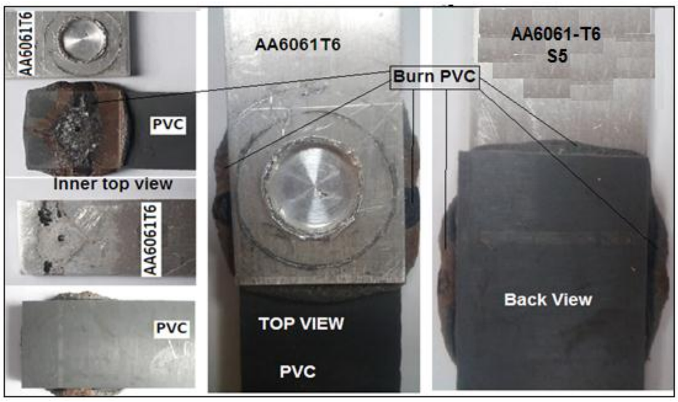

Figure 11. Surface features of the sample 5 of the AA6061-PVC joint.

The macro structure test was carried out to examine the behaviour of the re-solidified polymer and aluminium fragments through the aluminium specimen hole. Then the samples of the optimum joining condition (maximum shear force) were next prepared for the macro inspections stage.
figure 12 shows the cross sections areas of the FSpJ samples. Were A slight deformation occurred on the surface of Al alloy. The polymer in a narrow area adjacent to the interface was melted during the friction process. The molten polymer transfer through the holes of the aluminum samples surfaces and mixed with the aluminium fragments. After that the polymer re-solidified under the applied pressure provided by the deformed aluminum by the tool. The aluminum specimen and polymer were bound together during the FSpJ process by means of the mechanical interlocking[13]. Defects such as small voids were detected at the boundary interfaces between the two materials. Moreover, the re-solidified polymer of joint type AA6061-T6/PVC exhibited voids at the surface of the re-solidified polymer. The macro images indicated that the molten polymer was fully penetrated and filled the aluminium specimen with the presence of the aluminium fragments. Also, the embedded fragments through the re-solidified polymer exhibited different size. While, the aluminium fragments distributed with a non-homogenous shape through the aluminium specimen hole. The entrapped aluminum fragments in the re-solidified layers of the polymer were showing different thickness depending on the joining parameters, which determined the joint strength.

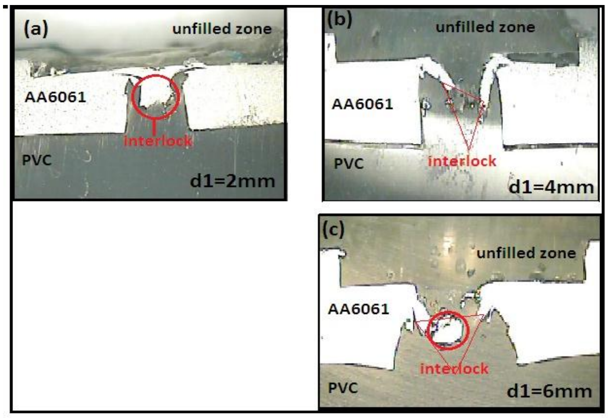

Figure 12. Cross-section of joints at different lower hole diameter: a)2mm, b)4mm, c)6mm.

3.4 Microstructure examination

The joints microstructure of the composite materials (re-mollified polymer with the Al fragments) inside and outside the hole of the aluminum specimen are shown in figures 13. It was observed that the Al fragments were distributed in different sizes from the aluminum slag and entrapped in the re-solidified layer of the polymer through the cross-sections of the joint's holes. The interface line between the polymers and aluminium hole surface was due to the mechanical interlocking between the aluminium pores and the polymer. However, the presence of the voids was detected in the PVC which caused a weakness in the joint area and reduction to the mechanical properties of AA6061T6-PVC joints. Also, it was observed that irregular re-solidification zone obtained in AA6061T6- PVC joints, which was distributed in an irregular form due to the presence of the defects such as voids. Those voids were formulated in the hole and beneath the interface between Al alloy and polymer After the joining process. macro, micro and nano-mechanical interlocks between the Al- fragments and melted/ re-solidified polymer matrix at the stir zone and inside the holes of the joint. The interfacial chemical reaction supported by the formation of nano-scale pores inside the hole and metal surface at the interface, and the secondary van der Waals joining were suggested as the main joining mechanisms that led to a significant improvement in the mechanical properties of the joints[14].

Figure 13. Microstructure of the joints cross-section of Al/PVC.

3.5 Scanning electron microscope (SEM)

The SEM examination was achieved in the joint cross-section at the aluminium hole and near to the interface line between the joined materials to examine the joining mechanism and the interface width between the two materials, as shown in figure 14. The samples that exhibited the optimum conditions were examined with the SEM. The SEM images, indicated that the joining zone of the holes exhibited a variation in the size of AL- fragments and different width of layers of the interface joint. The interface width at the joints zone between the PVC and AA6061-T6 exhibited the following values: 9.057, 31.24, The re-solidified polymer diffused and penetrated through the aluminium pores successfully.

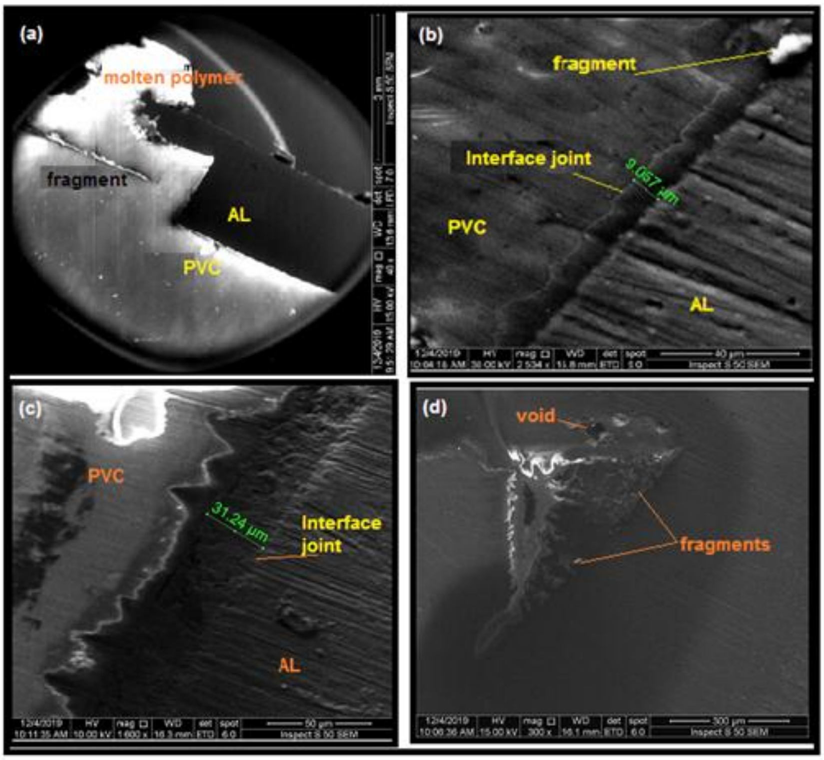

Figure 14. SEM images at the optimum conditions hols and interface for Al – PVC joints at magnification of (a) 3mm (b) 40µm (c) 50µm (d) 300µm.

3.6 Energy dispersive spectroscopy (EDS) analysis:

The EDS analysis provided useful information on anodizing pre-treatment alternations of the chemical composition of the aluminium surface. Such changes in the chemical composition and an oxide layer generated on the surface influence the adhesion between the aluminum and polymer, and hence the mechanical performance of the joints.

The Al - PVC EDS analysis indicated that the joint zone consists of the main element of (Al, Cl, Si, O and a small amount of Mg) across the friction lap joining of aluminum to polymer joints. Figures 15- show the EDS spectra from different regions which represents the element identification of AA6061T6-PVC joints. This possibly suggests the occurring of a Van der Waals reaction between the aluminum and polymer during joining process the surface energy of metals and polymers are completely different.

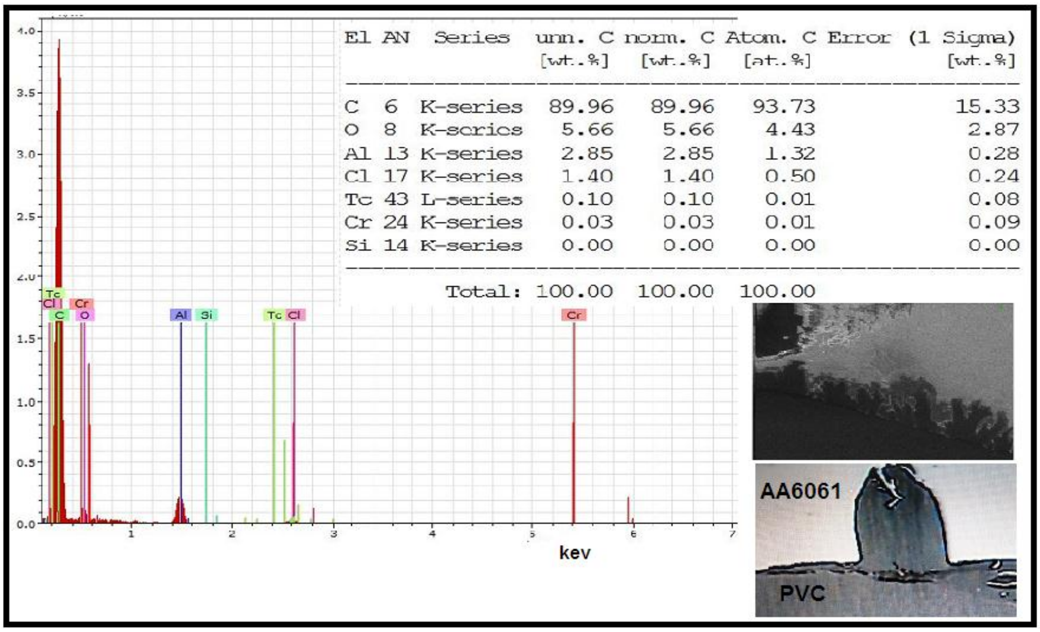

Figure 15. EDS line of the optimum condition for the interface of AA6061T6& PVC.

4. Conclusions

A friction spot joining technique was employed to join aluminum alloy AA6061-T6 to polyvinylchloride using a rotating tool to produce the necessary heat to melt the polymer and to achieved penetration through the aluminum specimen hole. The effects on the joint quality of the hole's diameter, tool rotational speed, plunge depth and pre-heating time were studied. The following principle findings and conclusions have been drawn:

1- The samples have all been successfully joined.
2- The joining process occurred by melting the polymer and penetrating it through the surface of the aluminum hole with a mechanical interlock and partial adhesive joining between the metal and the polymer.
3- The shape of the bubbles and distance between the reaction layers and the re-solidified polymer within the hole decreased the efficiency and the joint strength of Van der Waal's bonds.
4- The macro mechanical interlocking attributed to the primary strengthening effect.
5- The joints properties depended on the joined field, the parameters of the frictional process and the quantity of the aluminum fragments in the polymer re-solidified.
6- Increasing the volume fraction of the fragments in the re-solidified polymer, hole diameter of the aluminum specimen, tool rotating speed and plunging depth of the tool increased the joint strength for all the joined specimens.
7- The maximum shear force of the joined sample was observed at a rotating speed 1800RPM, plunging depth of 0.4mm, pre-heating time of 15 sec and a hole diameter of the aluminum specimen of 6mm with a value of 1664N.

References

[1] M. V. Gandhi and B. Thompson, *Smart materials and structures*: Springer Science & Business Media, 1992[1] M. V. Gandhi and B. Thompson, *Smart materials and structures*: Springer Science & Business Media, 1992.
[2] J. C. Williams and E. A. Starke Jr, "Progress in structural materials for aerospace systems," *Acta Materialia*, vol. 51, pp. 5775-5799, 2003.
[3] T. Dursun and C. Soutis, "Recent developments in advanced aircraft aluminium alloys," *Materials & Design (1980-2015)*, vol. 56, pp. 862-871, 2014.

[4] S. Amancio, *Friction Riveting: development and analysis of a new joining technique for polymer-metal multi-materials structures*: GKSS-Forschungszentrum, 2007.
[5] G. Meschut, V. Janzen, and T. Olfermann, "Innovative and highly productive joining technologies for multi-material lightweight car body structures," *Journal of Materials Engineering and Performance,* vol. 23, pp. 1515-1523, 2014.
[6] C. Rodrigues, L. Blaga, J. Dos Santos, L. Canto, E. Hage Jr, and S. Amancio-Filho, "FricRiveting of aluminum 2024-T351 and polycarbonate: Temperature evolution, microstructure and mechanical performance," *Journal of Materials Processing Technology,* vol. 214, pp. 2029-2039, 2014.
[7] M. Sabetzadeh, R. Bagheri, and M. Masoomi, "Study on ternary low density polyethylene/linear low density polyethylene/thermoplastic starch blend films," *Carbohydrate polymers,* vol. 119, pp. 126-133, 2015.
[8] P. C. Lodi and B. Souza, "Thermo-gravimetric analysis (TGA) after different exposures of High Density Polyethylene (HDPE) and Poly Vinyl Chloride (PVC) geomembranes," *Electronic Journal of Geotechnical Engineering,* vol. 17, pp. 3339-3349, 2012.
[9] F. Khodabakhshi, M. Haghshenas, S. Sahraeinejad, J. Chen, B. Shalchi, J. Li, *et al.*, "Microstructure-property characterization of a friction-stir welded joint between AA5059 aluminum alloy and high density polyethylene," *Materials Characterization,* vol. 98, pp. 73-82, 2014.
[10] G. Michael W.Allsopp, Vianello, "Polyvinyl chloride," *Polymer Science Engineering* 1992.
[11] I. T. Abdullah, S. K. Hussein, and A. K. Hussein, "Joining of AA6061 to polyvinyl chloride via hot extrusion," *International Journal of Structural Integrity,* 2019.
[12] S. Mallakpour and S. Rashidimoghadam, "Investigation on morphology, properties, and applications of hybrid poly (vinyl chloride)/metal oxide composites," in *Hybrid Polymer Composite Materials*, ed: Elsevier, 2017, pp. 343-377.
[13] N. M. A. A. M. K. H. Sabah, "Effect of anodizing on the hot pressing of aluminum alloy AA6061-T6 to different types of polymers”," *Engineering Journal,* vol. 21, 29/12/2017 2017.
[14] F. Khodabakhshi, M. Haghshenas, J. Chen, B. Shalchi Amirkhiz, J. Li, and A. Gerlich, "Bonding mechanism and interface characterisation during dissimilar friction stir welding of an aluminium/polymer bi-material joint," *Science and Technology of Welding and Joining,* vol. 22, pp. 182-190, 2017.