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FRICTION STIR SPOT JOINING OF AA6061-T6 TO FIBER GLASS COMPOSITE MATERIAL

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Abstract- Manufacturing of components utilizing thermoplastic, fiber-reinforced polymer and other light-weight metals became more common throughout the industrial revolution as a result of the enormous degree of flexibility in producing complicated designs. It is required to connect lightweight components to create diverse structures. Traditional welding methods are ineffective for joining these materials. Polymer-metal hybrid structures may be joined via Friction Spot Joining. Joining of aluminum AA6061-T6 fiberglass reinforced composite material has been demonstrated in this study using friction stir spot joining FSJ. Feed rate, plunge depth, and tool rotation speed were all taken into consideration. Joint temperature and shear strength were studied using a design of experiments technique. According to this research, selecting the proper FSJ processes and parameters is critical. The strongest joint in the batch had an ultimate lap sheer force of 1400 N. This was considered excellent mechanical performance. The study's findings formed the basis of the paper's final comments.

Keywords: FSSW, Al, Composite Material, Fiberglass.

1. INTRODUCTION

A composite material in addition to its conventional usage in aircraft, new trends and breakthroughs in cost reduction and production have expanded their uses in transportation, industry, and many other sectors. Composite materials are increasingly becoming a part of an engineer's day-to-day design requirements as consumers' demands for lighter components rise. Components made of composite materials are utilized in a broad range of applications to decrease weight and give superior environmental resistance, enhanced aesthetics, more design possibilities, and increased stiffness to weight ratio. A vast variety of composite materials are made using polymeric components as a matrix. For more than half a century, the aerospace and maritime sectors have relied on the low density, moldability, and environmental resilience of fiber-reinforced polymer (FRP). Engineering infrastructures have a lot to gain by using this particular class of materials [1].

Lightweight materials like aluminum and magnesium alloys and fiber-reinforced polymers are also becoming more commonplace in the transportation sector. The necessity to reduce weight to fulfil the new, more stringent environmental rules aimed at reducing greenhouse gas emissions supports this [2]. A favorable side effect of using innovative lightweight constructions is that they reduce fuel consumption and extend vehicle operating range without sacrificing structural mechanical performance [3], [4]. Automotive and aerospace applications often utilize distinct structural materials due to both technical and economic considerations in the production of big structures. Advanced connecting methods are needed for this new multi-material construction paradigm. It is difficult to join composite metal structures because of the considerable material dissimilarity in characteristics, such as heat resistance and thermal expansion coefficient [4].

There are currently no cost-effective, high-performance, or environmentally acceptable methods for joining composite metal structures [5]. As a result, there is a market for innovative joining technologies to be researched. Van der Waals forces hold big molecules together in polymer systems, while high-energy bonding in metals creates tightly packed crystalline structures. Due to the tendency of metals to form clusters rather than mix evenly when coupled with polymers, this means that the solubility of metal in plastics is much lower. The melting point of a polymer is much lower than the melting point of a metallic substance. As a result, before metal melting, polymers tend to dissolve (softening/ductility) [6]. However, it is possible to join composite materials with metals by heating the polymer to a temperature close to its melting point.

Glass fiber-reinforced polymers (GFRP) have recently been used in the building of emergency bridges [1]. Multi-material low weight novel structures for engineering applications can only be realized if several lightweight materials, such as metallic and polymeric, can be joined together [7]. Automobile and aerospace constructions manufactured from light-weight dissimilar materials such as fiber-reinforced polymers (FRP) and aluminum or magnesium alloys may be produced using this technology [8]. In the industrialization of composite structures, the joining of composite materials to one other or other materials, such as metal, wood, and plastic, is essential.

Metal and polymer couplings have been researched using a variety of ways. Welding, adhesive bonding, and mechanical fastening are all examples of these techniques [9]. A successful and robust joint between polymer and metal may be confirmed by using any of these methods alone or in combination with each other, as needed. It's important to keep in mind that different joining methods have different benefits and drawbacks, therefore it's important to choose the right one for your project [10].

The production of adhesive forces between the polymeric material and the workpiece is required for adhesive bonding, which is a method of joining solid materials together. This technique is popular because it can create joints that can sustain both a constant and a varying load. The inability to separate neighboring pieces without destroying one of them is a drawback of this procedure. The inability to forecast the long-term longevity of the joint due to exposure to moisture and heat is the most crucial obstacle in restricting the usage of this technology [7].

Many different types of fasteners may be used in mechanical assembly to join components of different materials together. The simplicity with which the parts may be separated and the lack of requirement for surface preparation are two of the advantages of this technology. The drawbacks of this procedure include an increase in the weight of the item, the risk of corrosion, and the chance of harm to the piece itself. In contrast, mechanical fastenings have a limited ability to seal. Bolt holes, which are present in constructions, reduce the cross-sectional area as stress increases. Cracks in composite materials occur as a result of the drilling procedure used to create bolt holes [11].

Having a variety of materials to work with makes constructing the design more difficult. Adhesive bonding and mechanical fastening, the two most common joining methods, are sometimes inadequate to meet industrial demands. Consider the likelihood of catastrophic failure and how to prevent it while designing multi-material joints for transportation [12]. In the fusion joining process, heat is used to produce the joint in the welding procedure. Using this technology, a solid-state junction may be created with little or no microstructural changes, and it works with both comparable and different materials. Metal and plastic are difficult to weld because of their very different characteristics.

The weaker component is more likely to fail in hybrid systems if there is a considerable disparity in mechanical characteristics between the joining partners. Figure 1 depicts the ASTM D5961-specified forms of bolted joint failures [13]. The catastrophic failure modes include tear-out, shear-out, cleavage, and net tension. On the other hand, bearing failure is induced by the material buckling and only gradually causes the load sustainability loss. Weakening with time When it comes to mechanical fastening, the unpredictability of a catastrophic failure is avoided as much as possible by using mechanisms such as bearings. Engineers can design the geometric relations of the structure to induce a most likely failure mode when taking into account this preference.

Figure 1. Bolted joints Failure modes according to ASTM: D5961[13]

Friction Spot Joining, often known as FSpJ, is an alternative method for manufacturing metal-polymer overlap spot junctions that were invented and granted a patent by Helmholtz-Zentrum Geesthacht in Germany [14]. The friction spot welding technique, which may be utilized to join thermoplastics and metal [15], is the foundation of this method.

In FSJ of metal-thermoplastic fiber-reinforced composites, there are two primary bonding mechanisms [16]: (1) Due to the micro-scale polymer filling of metal surface, cracks and holes in combination with a partial plasticization of metal at the interface, adhesion forces are generated and (2) nub creation causes macro-mechanical interlocking. Both of these bonding mechanisms are caused by nub formation. During the process of combining the two pieces, frictional heat is created, and it is conducted from the metal to the composite by employing conduction. This causes the polymeric matrix thin layer to melt. After the consolidation process is complete, the molten layer causes adhesion forces to be generated between the connecting pieces. Simultaneously, Local micro- mechanical fiber anchoring by the metal may occur when fiber bundles are exposed to the plasticized metal, leading to an increase in the amount of micro-mechanical interlocking [16].

Joining forces, plunge depth, joining time, and tools rotation speed are the four most important FSpJ process parameters that may be adjusted. The bonding processes and, as a result, the joint mechanical performance and microstructure are directly influenced by these process factors. In summary, joining time and rotating speed decide the amount of input of heat and the viscosity of the polymer molten layer that is formed. The metallic nub's form and depth are determined by the plunging depth, while the joining force keeps the plates in close contact and regulates the polymer molten layer flow.

Joints of hybrid composite metal made of lightweight metals such as aluminum AA6181, aluminum AA2024, and magnesium AZ31 with carbon and glass fiber-reinforced thermoplastic composites have been proven to be technically feasible using the FSpJ technique [17].

When compared to previous polymer-metal hybrid joints made using state-of-the-art procedures, these joints demonstrated either the same level of or an even higher level of mechanical strength.

Goushegir, et al. [16] published research that demonstrated the applicability of FSpJ to the aluminum alloy AA2024 as well as the carbon fiber-reinforced poly (phenylene supplied) (CFPPS) laminate. They found that the consolidated polymer bonding area had a link with the strength of lap shear. They put out a straightforward model that illustrates the various bonding zones and the respective contributions of each to the strength of the joint.

Esteves, et al. [18] FSpJ is an effective method for joining aluminum alloy AA6181-T4 and carbon fiber-reinforced PPS. They found that by conducting pre-treatment of the metal surface to boost adhesion forces, the joint mechanical efficiency may be raised by around 160%.

Recently, many techniques have been developed to attach various polymers to metals in a way that maintains the polymer's strong mechanical qualities while reducing the weight and cost of the junction. I.T. Abdullah, et al. [6], used the friction spot approach to fuse PVC and AA6061 via the process of hot extrusion. The joint achieved a shear strength that was 7.5 times greater than the underlying material (PVC).

Abdullah and Hussein [1], a bonding mechanism that included pre-drilled AA7075 samples was re-filled with HDPE using the friction spot approach was adopted. According to the findings, the depth of the plunge had the greatest influence on the amount of heat that was introduced, and the linked samples were unsuccessful, resulting in the shearing of the polymer layers without pullout. Derazkola, et al. [19], used the FSW approach to successfully connect poly-methyl-methacrylate to AA5058 sheets. The findings showed that the joint efficiency was dictated by the mechanical interlock between the two sheets, reaching a maximum of 60%.

F. Lambiase, et al. [20], used assisted friction to attach AA5053 to polyvinyl chloride sheets and found it to be successful. The joint's efficiency was enhanced to 97% by using wood clamping to prevent energy loss. Karami Pabandi, et al. [21], the first time the melted carbon fiber-reinforced polypropylene was used to fill a pre-threaded AA5052 hole utilizing the FSW joining process. At the interface, C, Al, and O elements were found using SEM. As the rotational speed rose, the joint's maximum shear strength reached a value of 80%. Shahmiri, et al. [22], tested if friction stir lap joining could be used to join AA5052 to polypropylene. Al, C, and O made up the contact between aluminum and polymer. The joint shear strength was reduced by increasing the heat input.

Ratanathavorn and Melander [23], AA6111 and polyphenylene supplied were joined using the FSW method. Using a mechanism of mechanical interlock, the molten polymer and Al chips were mixed. Goushegir, et al. [24], studied the FSJ variable's effect on the CF-PPS to AA2024. Joint shear strength was more strongly affected by tool pressure and revolving speed than by plunging depth. Nagatsuka, et al. [25], adopted friction lap joining to successfully attach the AA5052 with the carbon fiber-reinforced thermoplastic. An interfacial magnesium oxide layer was formed as a means of connecting the two pieces. Khodabakhshi, et al. [26], employed the friction stir (FSW) method with a butt configuration, AA5059 was welded with HDPE. According to the results of the microstructure analysis, the welding was accomplished using a combined secondary bonding and mechanical interlocking. Goushegir, et al. [16], joined the carbon fiber-reinforced polyphenylene supplied (CF-PPS) to AA2024 via an FSJ approach. Sandblasting the aluminum surface resulted in an enhancement in the mechanical characteristics of the joint. Yusof, et al. [27], fused polyethene with AA5052 using the (FSJ) method and proved it to be an effective procedure. According to the findings, increasing the tool's plunging depth boosted the joint's tensile shear strength.

This study aimed to join aluminum alloy AA6061-T6 with fiber glass polyester-based composite material using friction spot joining. In this technique, a combined effect of applied pressure and heat input was the main factor used to achieve the joining technique. A rotating tool was adopted to accomplish the joining process. The effect of rotating speed, feed rate and tool plunging depth on joint quality was studied.

2. EXPERIMENTAL WORK

2.1. Materials

Aluminum alloy (AA6061-T6) and a composite material (four fiber glass layers, 50% (204 g), polyester 50% (204g)) sheets were selected to prepare specimens with a thickness of 1.65 and 2.75 mm, respectively. Table 1 lists the mechanical properties of Aluminum alloy AA6061, its chemical composition in Table 2, and the physical and mechanical properties of composite material are summarized in Table 3.

Table 1. Mechanical properties of AA6061-T6

	Yield stress (proof stress 0.2%) MPa	Ultimate stress (MPa)
Standard value [6]	>241	>289.3
Actual value	299.7-302.5	339.6-3417

Table 2. Chemical compositions of AA6061-T6

	Cr%	Ti%	Zn%	Mg%	Mn%	Cu%	Fe%	Si%	Al%
Actual value	0.16	0.06	0.04	0.9	0.13	0.21	0.42	0.76	Bal.

Table 3. Composite material properties

Thermosetting polymer	Density ($\times 10^2$ kg/m³)	Tensile strength (MN/m²)	Compressive strength (MN/m²)	Young's modulus (MN/m²)
Polyester	11	31-70	90-240	2800-7000

2.2. Sample Preparation

The samples were prepared with a width and length of (25 and 100) mm, respectively as shown in Figure 2.

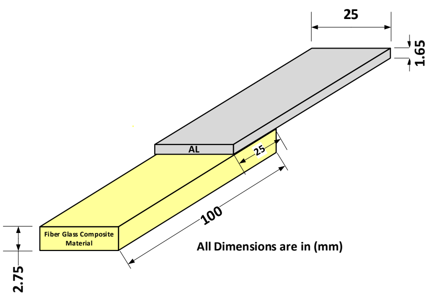


Figure 2. Sample shape and dimensions

2.3. Process of Joining

The joining method was executed in 2 stages: the first stage involves pre-heating the aluminum specimen with the rotating tool and plunging the tool into this specimen, causing heat generation in the lap joint region at the aluminum alloy's upper surface by the friction force between the tool and aluminum sheet, leading to a temperature increase at the part joint and melts the composite material, this leads to polymer material melting. The molten polymer diffuses under the tool by applying pressure during the joining process. A milling machine is utilized to conduct the joining process as illustrated in Fig. 3. In the second stage, the pressure was applied by pushing the revolving tool down the aluminum alloy at a plunge depth. A K-type thermocouple was utilized for temperature measuring. It was located at 12.5 mm from the centerline of the rotating tool.

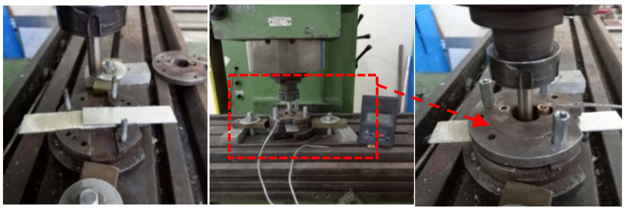


Figure 3. Joining process

2.4. Design of the Experiments

The influence of three parameters on joining quality was investigated; rotating speed, Feed rate, and tool plunging depth. Three values were studied for every joint parameter. The design of experiment (DOE) technique was utilized to design the experiments by the Taguchi technique, with the asset of the Minitab software, a statistical method was utilized to investigate the influence of joining factors on the joint behavior. Therefore, nine experiments were designed with various parameter values to investigate the joint quality between the two materials (aluminum with composite specimens), as described in Table 4. The joined samples of the aluminum together with the composite materials were investigated by the tensile.

Table 4. Taguchi design

Sample No.	Rotating Speed (RPM)	Feed rate mm/min	Plunging Depth (mm)
1	560	16	3
2	560	20	3.5
3	560	25	4
4	710	16	3.5
5	710	20	3
6	710	25	4
7	900	16	3.5
8	900	20	4
9	900	25	3

3. RESULTS AND DISCUSSION

3.1. Joint's Shear Force

To examine the joint quality and investigate the effect of process parameters on the joint's shear force, a shear force test was performed on the joined samples. The shear force is illustrated in Figure 4. In samples No. 4 and 9, the joint's shear force achieved a minimum and highest sheer force of 750 and 1400 N, respectively.

The DOE was used to examine the joint shear forces, as displayed in Figure 5. The main effect plot, Figure 4a, showed that decreasing the tool's plunging depth, decreasing the rotational speed to 710 RPM, and increasing the feed rate to 20 mm/min increases the sheer force of the joints [28]. This can be consolidated because, with the assistance of the tool's applied pressure, a higher feed rate can improve the interlock at the joint surface between the two materials. According to the Pareto chart, the tool's depth of plunge has the maximum influence on the shear force, then by the tool's rotational velocity and feed rate [29].

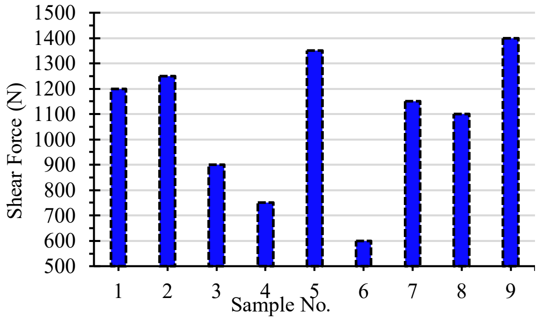


Figure 4. Shear forces of samples

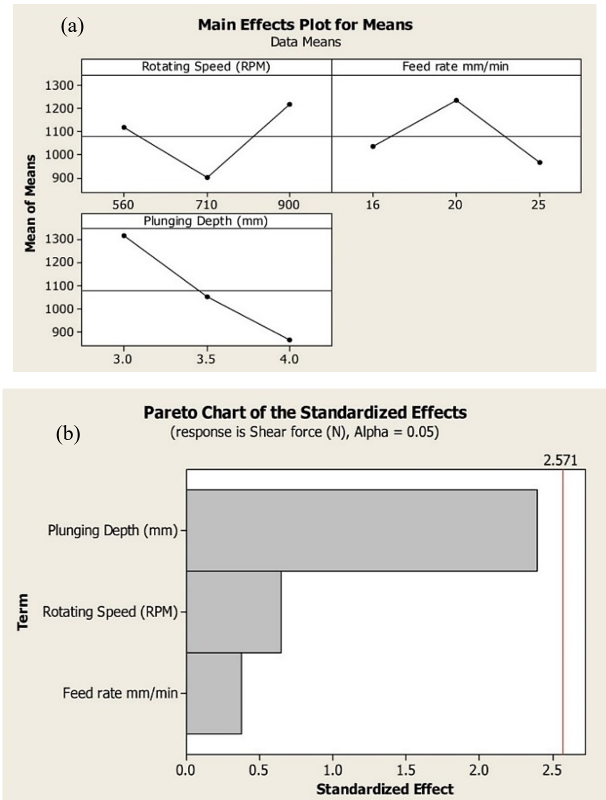


Figure 5. Analysis of shear force by DOE (a) main effect plot (b) Pareto chart

Equation (1) was estimated utilizing the Minitab program and the design of the experimental approach. The formula describes the shear force as a function of the process parameters.

$$\begin{aligned} &\textit{Shear Force}(\mathrm{N}) = 2315.91 + 0.354\ \textit{Rotating Speed}(\mathrm{RPM}) + \\ &+8.22\ \textit{Feed rate}(\mathrm{mm/min}) - 474.654\ \textit{Plunging Depth}(\mathrm{mm}) \end{aligned} \quad (1)$$

Figure 6 was plotted according to the DOE analysis; the lap joint's shear force is depicted separately. In the case of (rotational speed, and plunging depth), as displayed in Figure 5a, raising the rotational speed to 900 RPM and decreasing the plunging depth to 3 mm resulted in a uniform rise in the shear force. When one or both of the plunging depth and rotating speed of the tool increased, the shear force rose uniformly, as illustrated in Figure 5 b. This could be because the rotating speed produces uniform input heat, resulting in the formation of a uniform intermetallic compound.

The sample shear test was influenced by process parameters (rotational speed, feed rate, and plunging depth) with the maximum shear force occurring at rotation speeds of 900 rpm. At the same time, the minimum shear force for all examined samples is at rotation speeds of 710 rpm. Knowing that all of the samples studied have the same diameter hole in the aluminum alloy.

3.2. Process Temperature

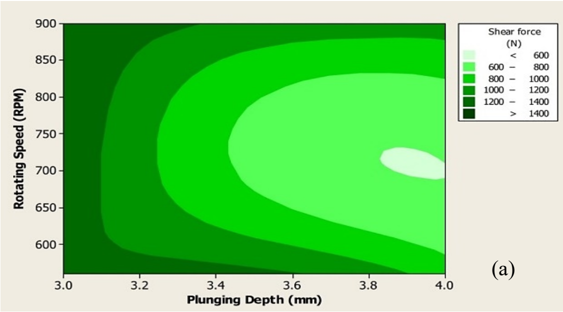
The highest temperature for each sample was measured during the joining procedure and recorded in Figure 7. The process temperature reached a minimum of 72 °C and a maximum of 118 °C, respectively. Samples No. 3 and 7 were joined at a maximum rotational speed, regardless of the tool's plunging depth and feed rate. As a consequence, increasing the tool's revolving velocity raises the process temperature [28]. This can be explained by the fact that the increment in the rotating speed raises the rotating friction between the shoulder surface and the material sample. DOE was used to examine the effects of the process parameters, as shown in Figure 8. The tool's depth of plunge had the maximum influence on the process temperature [30], followed by the feed rate and revolving speed, according to the Pareto chart (Figure 8a). The main effect figure indicated that raising the plunging depth, rotation speed to 710 RPM, and feed rate to 20 mm/min raises the process temperature. The quantity of solidification of the upper surface of the specimen can be increased by increasing the rotation speed, which lowers friction between this surface and the shoulder surface. As a result, increasing the rotating speed above 710 RPM lowers the process temperature.

Additionally, Equation (2) was used to evaluate a simple formula between the joint's process temperature and the process parameters.

$$\begin{aligned} &\mathit{Process\ Temperature}\left(°\mathrm{C}\right) = 5.1 + 0.0073\ \mathit{Rotating\ speed}\left(\mathrm{RPM}\right) - \\ &- 1.62\ \mathit{Feed\ rate}\ (\mathrm{mm/min})\ + 34.85\ \mathit{Plunging\ depth}\left(\mathrm{mm}\right) \end{aligned} \tag{2}$$

3.3. Joint's Surface Feature

Table 5 exhibits the surface characteristics of each sample. The surface of the materials specimen before testing is shown in the first column. Under the influence of the higher applied force and heat input, the aluminum metal (under the tool shoulder) displayed a spiral shape in the majority of the samples. This displays that the aluminum metal achieved a solid state throughout the joint procedure. The surface of the two material specimens of the tested samples that had the tool trace is shown in the second column. The fractured surface of samples displayed that the fracture mode failed by pull-outing and shearing of the aluminum metal from the composite material specimen at the joint area.



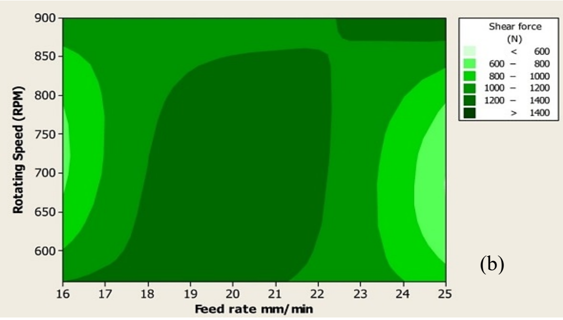


Figure 6. Analysis of process parameters, (a) relation between Rotating speed and plunging depth, (b) relation between Rotating speed and feed rate

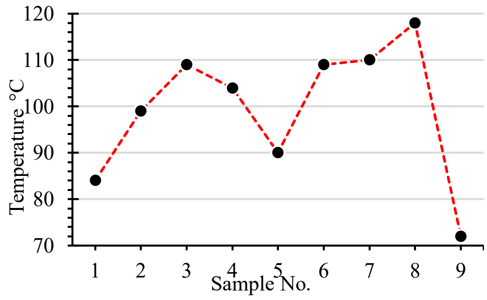
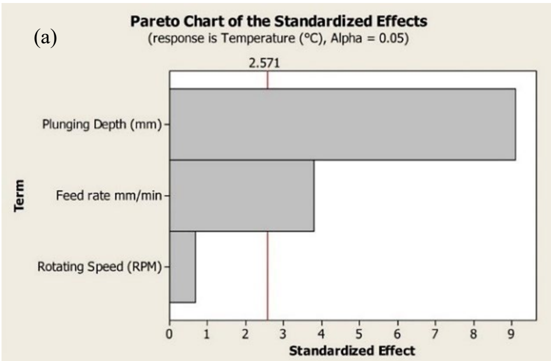


Figure 7. Maximum temperature for each sample



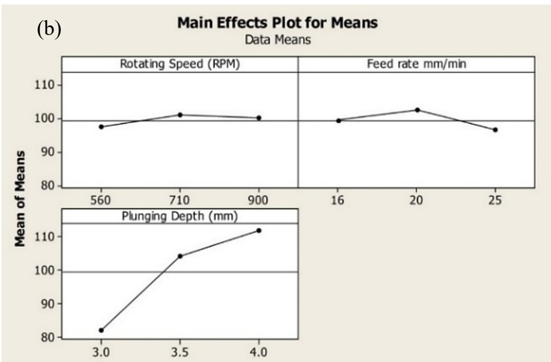
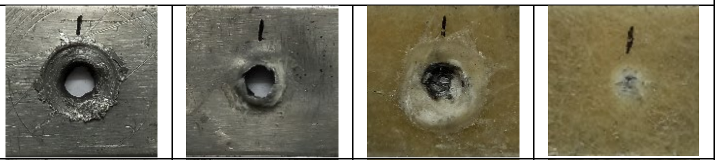
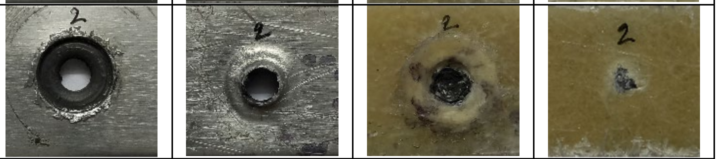
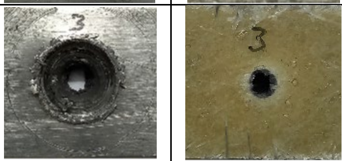
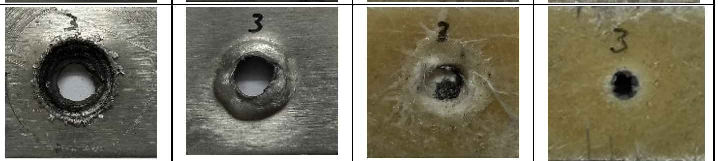
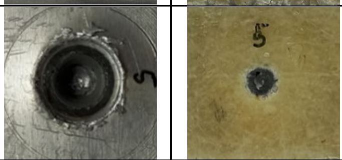
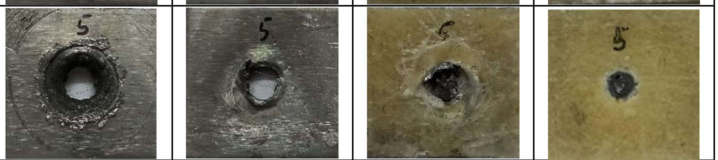
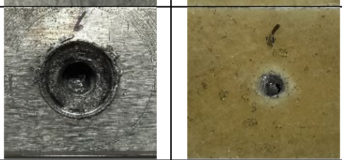
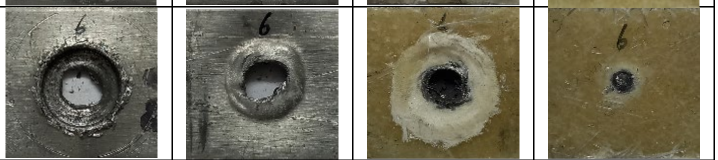
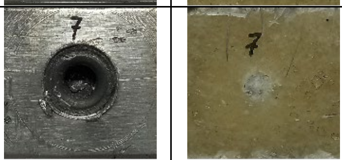
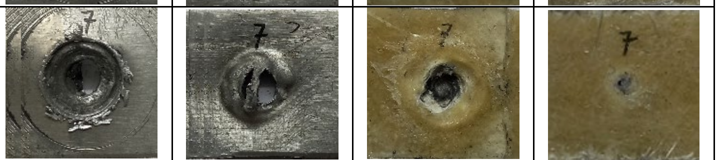
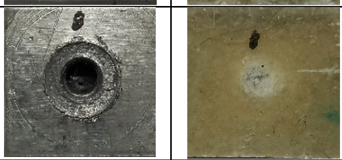
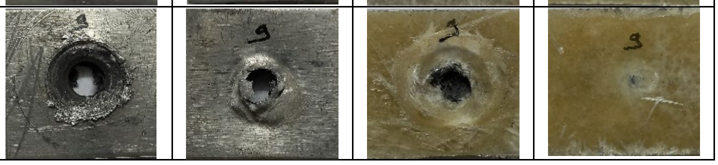


Figure 8. Analysis of process temperature by DOE (a) main effect plot (b) Pareto chart

Table 5. Surface feature of the samples

No.	Before test	After test
1		
2		
3		
4		
5		
6		
7		
8		
9		

3.4. Relation between the Process Temperature and the Shear Force

The relation between the process temperature and the shear force exhibited that the joint's shear force reduces with rising the process temperature as shown in fig. 9. Because of their highly cross-joined structures, thermoset adhesives have no melting points and are thus suitable for high-temperature applications. Thermal oxidation induces chain scission of their molecules, which results in a decrease in the adhesive's strength, toughness, and elongation in the bulk. Due to the mismatch in coefficients of thermal expansion between the attached and adhesive, high service temperatures also result in internal stresses. According to the results of the investigation, the glue used to attach the FRP composite or the aluminum parts is weaker than previously thought. A thicker workpiece means a thicker adhesive layer, and this is the reason why. As a consequence, the bond stresses increase until the bond fails at a lower load than the adhesion fails, resulting in a lower failure point for the bond. However, the failure mode should be cohesive or within the adherent in well-bonded aluminum/FRP joints (FRP inter-laminar failure). Adhesive/adhesive contact failure indicates that a stronger binding is needed.

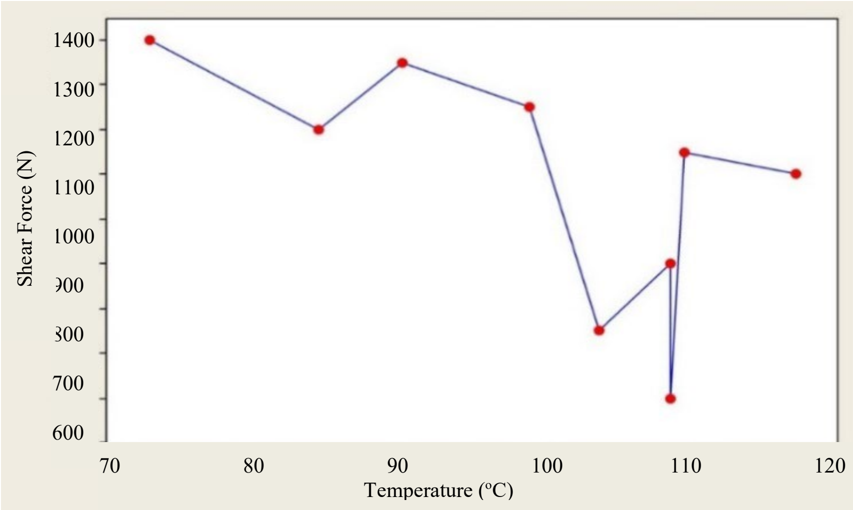


Figure 9. The relation between the process temperature and the shear force

4. CONCLUSION

Friction spot joining (FSpJ) process parameters had a significant impact on the mechanical strength of aluminum AA66061-T6/fiber-glass reinforced polyester hybrid joints. The produced joints had good mechanical properties, displaying maximum lap shear forces of 1400 N in the process of testing (condition 9). The following conclusions could be drawn as follows:

1) The joints' shear force was improved by lowering the tool's plunging depth, lowering the rotational speed to 710 RPM, and raising the feed rate to 20 mm/min.
2) The tool's depth of plunge had the maximum influence on the temperature.
3) The joints fractured in two types of modes: pull-outing and shear.
4) Raising the depth of plunging, revolving speed to 710 RPM and feed rate to 20 mm/min rose the process temperature.
5) The tool's plunging depth had the maximum influence on the joint's shear force, then by its rotational velocity and feed rate.
6) As the process temperature rises, the joint shear force decreases.

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