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Research Paper

Experimental Investigation of One-pass and Two-pass Friction Stir Welding Process of Aluminum Alloy 6061 with and without Copper Foil

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Abstract

In this research, conventional Friction Stir Welding (FSW) and two-pass friction stir welding were employed to weld AA6061-T6 alloy parts with a copper interlayer (copper foil). The study found that several factors significantly influence the strength and ductility of the welds. These factors include the number of welding passes, the presence or absence of a copper foil interlayer, the direction of tool rotation, and the tool movement direction in the second pass. The analysis revealed that the samples with the highest tensile strength and ductility were, in descending order, TP-D (Two-Pass, type D), TP-B (Two-Pass, type B), TP-C (Two-Pass, type C), TP-A (Two-Pass, type A), and CF-Cu (Conventional FSW with Copper interlayer), with the CF (Conventional FSW) samples serving as a baseline. The growth in tensile strength for these samples was 58%, 36%, 45%, 29%, and 21%, respectively, compared to the CF sample. Notably, the TP-D sample exhibited the highest growth in tensile strength, achieving a 58% increase relative to the CF sample, and its tensile strength efficiency was 89.3% compared to the base metal. Furthermore, the TP-D sample also showed the greatest improvement in ductility, with a 35% increase compared to the CF sample, and a ductility efficiency of 81.1% relative to the base metal.

Keywords

Friction Stir Welding, Double Pass Welding, Copper Interlayer, Aluminum Alloy, Weld Strength

1. Introduction

In general, two general categories of joints can be used in metals including mechanical joints and metallurgical joints. Each of these two categories includes specific techniques in their special categories. In general, according to the type of material involved in the joint, the scale of the structure, and the designer's expectations, the joint technique is selected and performed. It can be boldly said that the choice of technique is the most important step in metal bonding. Welding is one of the bonding techniques which is widely used in industries. Among many welding techniques, Friction Stir Welding (FSW) is a relatively new process for bonding metals such as aluminum, magnesium, and steel alloys in solid state [1]. Friction Stir Welding was first developed for aluminum. Current welding methods are not sufficient for welding aluminum alloys used in aerospace [2]. Some aluminum can be welded, but instead have a big problem with surface oxides, which are also expensive to remove. These issues caused the invention of the FSW. The main idea of friction welding is very simple [3]. One must consider a non-consumable rotary apparatus (a special pin). The two metals are firmly placed next to each other, and the pin enters the connection of the two metals and travels the length of the connection line with rotation [4]. The pin performs two main functions: Heating the piece by friction and moving the material to the connection. Heat is obtained by friction between the pin and the workpiece while changing to the plastic form of the workpiece. Concentrated heat softens the material around the pin and with the rotational movement of the pin, causes the material to move from the front of the pin to the back of the pin [5]. In FSW welding, the materials deform greatly at high temperatures and the final structure has fine grains causing desirable mechanical properties. As shown in Figure 1, the tool is placed at the seam of the two pieces and moves forward as it rotates. On one side, the linear velocity resulting from the rotation of the tool is added to the velocity of the tool, which is called the Advancing Side (AS). On the other hand, the linear velocity resulting from the rotation of the tool decreases the forward velocity of the tool, which is called the Retreating Side (RS) [6].

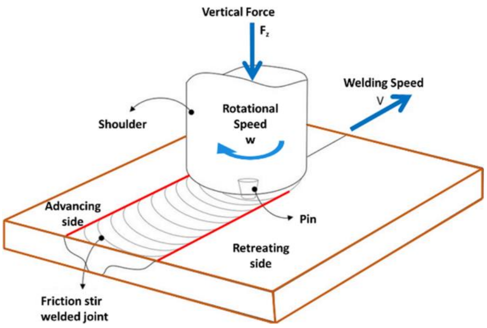

Figure 1. Schematic of the FSW process [7]

The rotational motion of the tool and its friction with the workpiece cause heat generation, decrease in flow stress, and increase the ductility of the material around the tool pin, and the translation motion of the tool causes the material to move from the front of the tool to its back. Loads are applied perpendicular to the sheets and parallel to the welding line by the tool to sweep the material softened by the friction heat around the pin. The action of "Stir" caused by the compressive and inhibitory forces of the tool creates a highly deformed region which upon cooling, forms a metallically fine-grained, oxide-free, and gas porosity-free zone [8]. As mentioned, FSW involves the complex movement of materials and plastic deformation. Welding parameters, tool geometry, and joint design have important effects on the material flow pattern, heat distribution, and finally the structure of the weld. In general, the variables of the FSW process are tool rotational speed, tool translation speed, force applied by the tool to the workpiece, workpiece thickness, tool (dimensions, geometric shape, tilt angle, tool material, and tool surface coating material), etc. [9]. Preheating and cooling parts in certain processes of FSW can be important. In cases with low melting temperatures, such as aluminum and magnesium, cooling can be used to reduce the overgrowth of recrystallized grains. In the following, a summary of some of the research that has been done so far in the field of one- and two-pass FSW and research in the field of aluminum and copper FSW has been presented. Li and Liu [10-12] investigated the RDR-FSW process of AA2019-T6 aluminum alloy. Based on their findings, it was found that the use of this technique significantly increases the mechanical and metallurgical quality of the joint and reduces the force and torsional torque required to perform the process. Shi et al. [13] modeled the RDR-FSW process thermo-mechanically. Based on the results, it was found that the use of the RDR-FSW technique results in relative symmetry in the pattern of heat distribution and plastic flow in the workpiece. The use of tandem tools was first proposed by Thomas et al. [14]. In this method, two tools move in a line with a reverse rotational direction and form the welding process. According to the research results, this method has significant advantages over the usual FSW process, such as reducing the clamping force and tensile torque, reducing process defects, and increasing joint efficiency. In another study, the effect of process parameters like tool translation direction and tool rotation direction on mechanical and metallurgical properties of two-pass FSW joint has been investigated the results showed that the ultimate tensile strength and the elongation percentage of the welded samples are dependent on the process parameters. In similar research, Manjunath et al analyzed the process parameters effects on hardness of welded specimens [15]. In the present study, two-pass FSW method has been used for welding. The use of one-pass linear FSW has its advantages as well as its disadvantages. In one-pass welding, due to the initial coldness of the workpiece, some volumetric and surface defects occur in the welding zone. These defects strongly affect the quality of the joint and reduce its efficiency. To address this shortcoming, the researchers introduced the two-pass FSW technique. In this method, after the completion of the first welding pass, the second pass begins. Based on the direction of rotation and the direction of tool movement in the second pass, this process is divided into 4 different types, each of which has significant differences in the way of creating material flow and the quality of joint with each other. One of the methods to strengthen the welding joint is to use copper reinforcement in the form of copper foils in the welding line. In the case of using a foreign dissimilar agent as a reinforcement in FSW, the distribution of this agent in the weld nugget must be well performed. Therefore, a suitable technique for FSW should be used. One of the techniques that can improve the distribution pattern of copper particles in the weld nugget is the use of the two-pass FSW technique. It should be noted that no research has been done in this field so far and the effect of increasing the number of welding passes on the mechanical properties of the welding sample with copper foil reinforcement has not been investigated. Therefore, in the present study, the effect of using one- and two-pass FSW techniques on the mechanical properties of 6061 aluminum alloy welding samples with and without copper foil has been investigated.

2. Materials and Methods

2.1 Materials

In this section, the materials and equipment used in the research are reviewed. This study aims to investigate the effect of using copper foil in the welding area on the mechanical properties of the joint resulting from two-pass FSW of aluminum alloy AA6061-T6. Since in the FSW process, very large thermal cycles are formed during the process, a tool must be used to maintain its function at such temperatures and its mechanical properties do not change. In the present study, H13 hot-worked steel was used to make the tool. Table 1 shows the chemical composition of H13.

Table 1. Chemical composition of H13 hot-worked steel

Chemical Composition (wt %)									
Cr	Mo	Si	V	C	Ni	Cu	Mn	P	S
4.75-5.5	1.1-1.75	0.8-1.2	0.8-1.2	0.32-0.45	0.3	0.25	0.2-0.5	0.03	0.03

To make the tool in the present dissertation, H13 hot-worked steel with a diameter of 20 mm and a length of 25 cm was prepared. After preparing the raw material, and designing and preparing the dimensional drawings of the desired tool, a CNC milling machine made was used for the tool reduction step. Figure 2 shows the tools designed to be used in the FSW process.

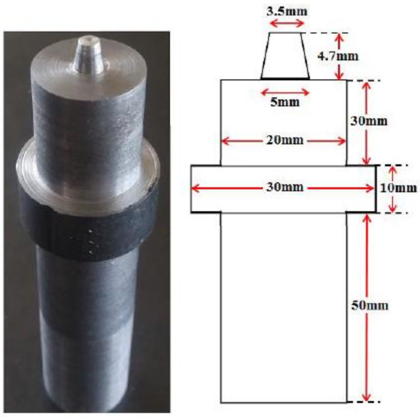

Figure 2. Tool used for FSW process

The tool undergoes relatively large mechanical and thermal stresses in the welding process. These stresses increase corrosion and defects in the tool. Thermal hardening is typically used to extend the life of the tools used. In the present study, the tool is made under a cycle of thermal hardening. To do this, the following steps were performed.

2.1.1. Preheating step

The preheating step of the tools took place in two different stages. In the first stage, the temperature of the tools increased with a temperature rate of 222° C/h to reach a temperature of 650 ° C. It should be noted that after reaching this temperature, the tool was kept at this temperature for one hour. In the second stage of the preheating, at the rate of 222 ° C/h, the temperature of the tools was increased from 650 ° C to 850 ° C and kept at this temperature for one hour.

2.1.2. Austinization step

In this step, the temperature increased immediately from 850 ℃ to 982℃, and the tools were kept at this temperature for 90 minutes.

2.1.3. Quenching step

In this step, a large tank of oil was prepared and the tools were taken out of the furnace and released in the tank. After cooling the tools to a temperature of 450℃, the tools were taken out of the tank and the cooling process was continued in the open air until they reached room temperature.

In the present study, AA6061-T6 aluminum alloy has been used to perform the FSW process. Following the main purpose of the present study, to improve the mechanical properties of the joint, pure copper foils with a thickness of 200 microns were used in the welding area. A schematic of the workpiece and metal foil is shown in Figure 3.

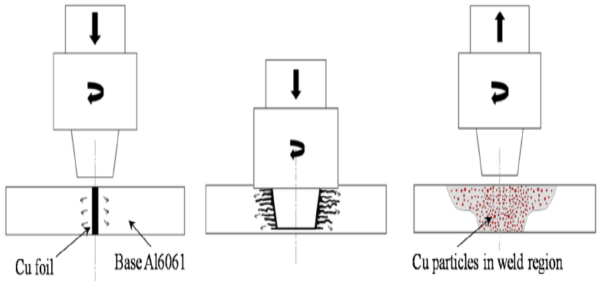

Figure 3. How to place copper foil in the welding area

Spectrometry was used to determine the chemical composition of aluminum alloy and copper foil. Tables 2 and Table 3 show the chemical composition and mechanical properties of AA6061 alloy.

Table 2. Chemical composition of AA6061-T6 alloy

Chemical Composition (%)								
Al	Mg	Si	Cu	Fe	Cr	Mn	Zn	Ti
Balance	0.81	0.61	0.29	0.2	0.13	0.03	0.02	0.01

Table 3. Mechanical properties of AA6061-T6 alloy

Yield Stress (MPa)	UTS (MPa)	Elongation (%)
268	330	17

Also, Tables 4 and 5 show the chemical composition and mechanical properties of copper foil.

Table 4. Chemical composition of copper foil

Al	Pb	Si	Cu	Fe	Ni	Zn
0.02	0.03	0.009	Balance	0.05	0.03	0.69

Table 5. Mechanical properties of copper foil

Yield Stress (MPa)	UTS (MPa)	Elongation (%)
280	353	28

Sheets were prepared in a thickness of 5 mm. For all samples of parallel FSW. Parts with dimensions of 5 × 50 × 120 mm^3have been used. Copper foils are also cut to dimensions of 120 × 5mm^2. Figure 4 shows the cut copper foils. To cut alloy parts, an industrial guillotine was used to smooth the edges of the parts so that there was no gap between the two edges of the workpiece during the butt-welding process.

Figure 4. Cut copper foils

After cutting and preparing the parts, a milling machine was used to perform the process of parallel FSW. In the present study, two-pass FSW has been used for welding. In this method, after the completion of the first welding pass, the second welding phase begins. Based on the direction of rotation and the direction of tool movement in the second pass, this process is divided into 4 different types, each of which has significant differences in the way of creating material flow and the quality of joint with each other. Figure 5 shows these 4 types of processes with the selected name for each method.

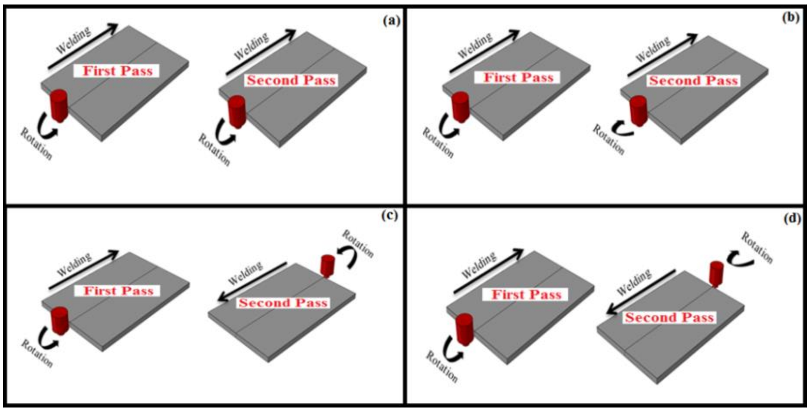

Figure 5. Two-pass FSW a) with the same direction of movement and the same rotation direction in welding passes b) with the same direction of movement and different rotation directions in welding passes c) with different direction of movement and direction of the same rotation in welding passes d) different direction of movement and different rotation direction in welding passes

Since the process parameters (translation speed and rotational speed of the tool) have a significant impact on the mechanical properties and microstructure of the welded parts, these parameters must be set in their optimal values. For this purpose, following the proposed values in the research [30], the translation speed equal to 60 mm/min and the rotational speed equal to 1180 rpm have been used. Also, the tilt angle of the tool was set equal to 2 degrees and the plunge depth was equal to 0.1 mm. It should be noted that the same process parameters were used for all samples.

2.2. Mechanical and metallurgical tests

To perform the tensile test, the tensile test apparatus from Santam, Iran (model STM-250) was used according to the standard. Since the surface conditions of the weld have not reached equilibrium because of thermal cycles in the 2 cm of the beginning and end of the welded area, tensile test specimens should be prepared after separating these parts from the rest of the weld specimen. The dimensions of the samples were prepared according to the standard, which is under the ASTM-E8M standard [16]. Figure 6 shows the dimensions of the tensile test specimen. It should be noted that two tensile test specimens were extracted from each welded specimen and the output results are based on the average results of these two specimens. All tensile tests were performed as a displacement control at a speed of 2 mm/min.

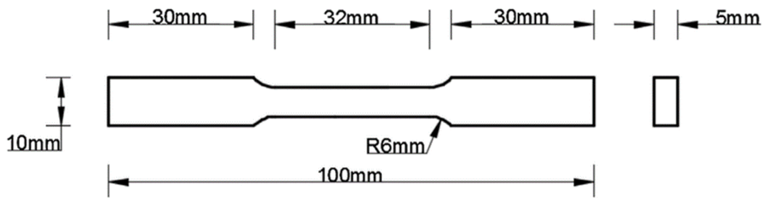

Figure 6. Dimensions of the tensile test specimens [16]

2.3. Micro-hardness test

Hardness is one of the inherent properties of a material. It can be considered as the resistance of a material to plastic deformation. The Vickers hardness test was utilized in this study and there are various standards for performing this test. In this test, a descending pyramid with a square base is used. The angle of the faces in front of the pyramid is 136 degrees. Vickers hardness can be obtained using Equation (1) [17].

$$HV = \frac{2F \sin\frac{\theta}{2}}{d^2} = \frac{1.854F}{d^2} \tag{1}$$

In this equation, F, d and θ indicate the value of force in kilograms, the average length of the diameter in millimeters, and the angle of the pyramid, respectively. The angle θ is typically 136 degrees. To perform the hardness test, a cross-section was made in the middle section of each of the welded specimens. Using sandpaper with grades of 220, 320, 500, 800, and 1200, the surfaces of the samples were sanded and prepared for a micro-hardness test. The micro-hardness test of the samples was performed by a micro-hardness device made by the Boehler Company in 30 seconds under a load of 50 gr at room temperature. To record the micro-hardness distribution, 16 points at a depth of 1.5 mm and perpendicular to the weld line were used for each sample. Figure 7 shows a sample prepared for micro-hardness testing.

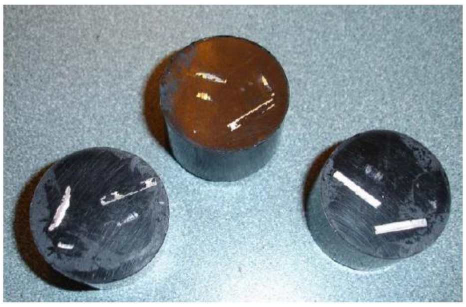

Figure 7. Schematic of several samples prepared for micro-hardness and microstructure testing

2.4. Metallography

In the present study, the samples were subjected to metallographic tests. In this manner, after welding, the parts were cut in a direction perpendicular to the process. Then, the samples were first polished by a rotating machine using alumina felt and powder, and finally, the samples were polished with a solution of diamond and felt liquid for the final polishing. The etching solution used for AA6061-T6 alloy was prepared by adding 1% by volume of hydrofluoric acid, 1.5% by volume of hydrochloric acid, 2.5% by volume of nitric acid, and 95% by volume of distilled water. The samples were etched in the prepared solution for 30 seconds. Zeiss light microscope was used to study the macrostructure and electron microscope was used to study the microstructure of the welding section.

3. Results and discussion

In the present study, the effect of using one- and two-pass FSW techniques on the mechanical properties of 6061 aluminum alloy with and without copper foil has been investigated. In this section, the results of experimental tests have been reviewed and discussed. One of the important cases in scientific studies is the appropriate naming of the studied samples. In the present study, two common FSW methods and two-pass FSW methods have been used to weld AA6061-T6 alloy parts with a copper interlayer (200-micron thick copper foil between two welding parts). A schematic of how the copper foil is placed as an interlayer is shown in Figure 8.

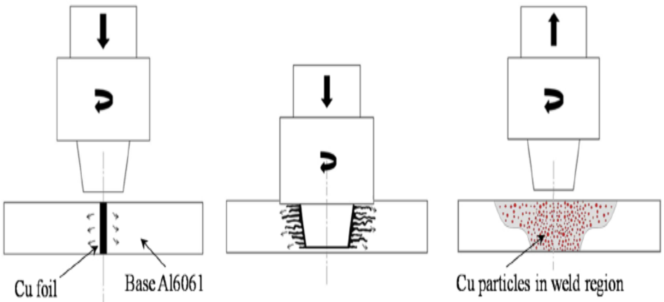

Figure 8. Schematic of how to place copper foil in the welding area

As mentioned, one- and two-pass welding have been used to weld alloy parts. It should be noted that two one-pass welding specimens have been performed, one of them without copper foil and the other one with the presence of copper foil to determine the effect of the presence and absence of copper foil on the mechanical properties of welded specimens. The welds of the two-pass made in the present study are different in two parameters: moving in the second pass and the tool rotation direction in the second pass. Based on the explanations provided, a total of six different types of welding samples have been performed. Normally, in the presentation of research works, appropriate naming should be done for the samples to avoid confusion when presenting the results. For this purpose, six samples studied in this study have been named. Table 6 presents the studied models and the name of each model.

Table 6. The samples studied in this research

Sample's Name	Welding Process	Interlayer	Rotation Sense in The Second Pass	Welding Direction in The Second Pass
CF	Conventional FSW	Without Cu Interlayer	-	-
CF-Cu	Conventional FSW	With Cu Interlayer	-	-
TP-A	Two-Pass FSW	With Cu Interlayer	Similar	Similar
TP-B	Two-Pass FSW	With Cu Interlayer	Opposite	Similar
TP-C	Two-Pass FSW	With Cu Interlayer	Opposite	Opposite
TP-D	Two-Pass FSW	With Cu Interlayer	Similar	Opposite

3.1. Macrography study of welded specimens

Two types of visual and macro inspections are commonly used to check the quality of welds. Some of the welds had surface defects that could be identified with the eyes, but the cross-section of the welds that looked to have high quality was deliberated. In the following, the results of the two types of inspections are reviewed.

- *Checking the weld surface*

Visual inspection of the weld cross-section is a simple, practical, and inexpensive method. Although a part is inspected through other non-destructive inspection methods (or NDTs), a proper visual inspection must be performed beforehand. Large surface defects can be identified with a simple eye inspection test. In this case, there is no need to perform other costly and complex tests. As a result, visual inspection can save time and money. Despite many advances in optical inspection, no electronic device or computer has been invented that can compete with the human brain. The experienced eyes of an inspection specialist are a valuable tool for a smart inspection. The first step in the FSW process is to deliberate the surface macrography of the welded specimens, also called visual inspection. In samples welded by FSW, common defects may occur on the surface and floor of the specimen, which can be identified by visual inspection of the weld surface. In this section, the surface of welded specimens is first deliberated to identify possible defects formed on the surface of these specimens. Figure 9 shows the welded specimens by one-and two-pass FSW. These specimens differ in the welding passes, the presence or absence of copper foil, the direction of tool rotation in the second pass, and the direction of movement of the tool in the second pass.

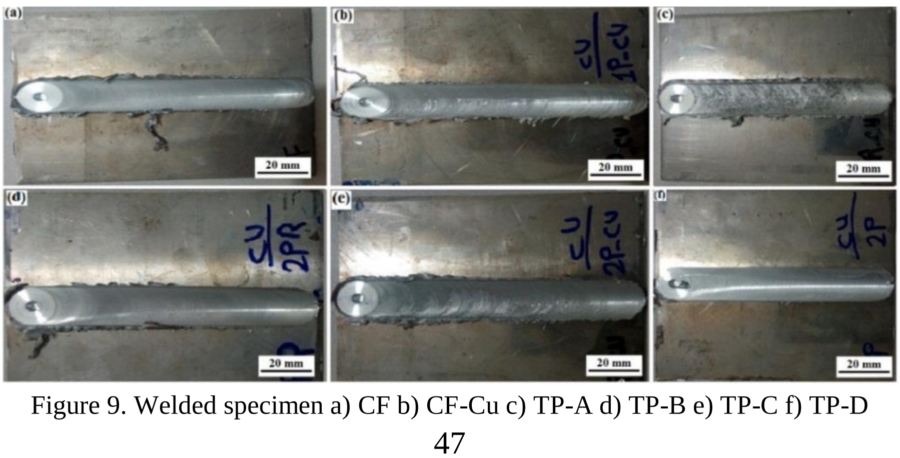

Figure 9. Welded specimen a) CF b) CF-Cu c) TP-A d) TP-B e) TP-C f) TP-D

As can be seen, regardless of the number of welding passes, movement of the tool in the second pass, rotation of the tool in the second pass, and presence or absence of copper foil, the surfaces of all samples are smooth and no "lack of fill" defect is created in the surfaces. There is also no visible hole on the surface of any of the samples. The only difference among the different welded specimens is the way the material protrudes at the edge of the weld. In Figure 10, the weld line image of the six samples is shown and the areas of material flow protrusion are highlighted.

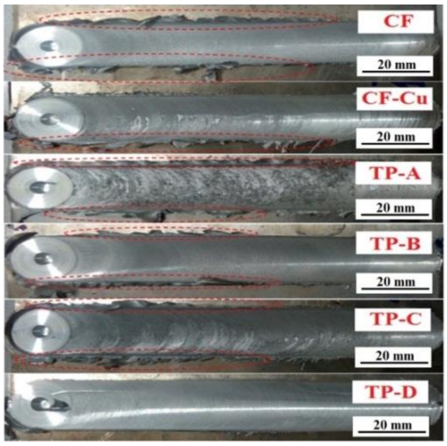

Figure 10. Protrusion defects (flash) of different sample surfaces

By observing the images of the welded specimen surfaces, it was found that by adding a secondary pass to FSW, the quality of the weld surface is improved and the protrusion defect is less formed in the specimens. The largest protrusion belongs to the CF welding specimen, which has undergone only one welding pass. An important and determining factor in the shape of surface flow is the heat and plastic flow of the material. By increasing the heat and plastic flow of the material due to the two-pass welding, a surface with less roughness is formed. As can be seen, the direction of tool rotation and the direction of movement of the tool in the second pass of welding also significantly affect the surface quality of the welded specimens. In samples where the AS and RS regions are inverted in the first and second passes (samples TP-B and TP-D), the least amount of material protrusion is created at the edge of the welding line, which is due to the correction of surface flow in the second welding pass. In these samples, the protrusions of the first pass in the second pass of welding are pumped into the welding line by the tool, which results in a better surface quality. In the TP-A sample, the burr is visible on the welding surface which is formed due to excessive heat or unbalanced heat distribution in the welding area. Since in this sample, two completely similar passes have been made consecutively on the workpiece, a lot of heat has been generated in the weld nugget. The core material of the weld protrudes from the weld surface due to heat and material flow, and after cooling, they appear as a burr.

- *Investigation of welding cross-section macrostructure*

If none of the mentioned defects are seen in the weld appearance, one cannot certainly say that the weld is healthy. To ensure this, a weld cross-section observation or so-called weld cross-section macrostructure is used for the final deliberation. Weld section macrostructure analysis is a method that is widely used to detect defects such as cavities, tunnels, and incomplete penetration of the weld. This method is also suitable for observing how the plasticized materials mix and identifying different areas in the weld in the FSW process. Three major defects Flash formation, Void formation, and Wormhole formation may occur in the welding section during FSW, and the main reason for them is improper heat and plastic flow. In the present study, to investigate the formation of these defects, the macrostructural images of the welding section of the samples have been used. Figure 11 shows the weld cross-section of the specimens.

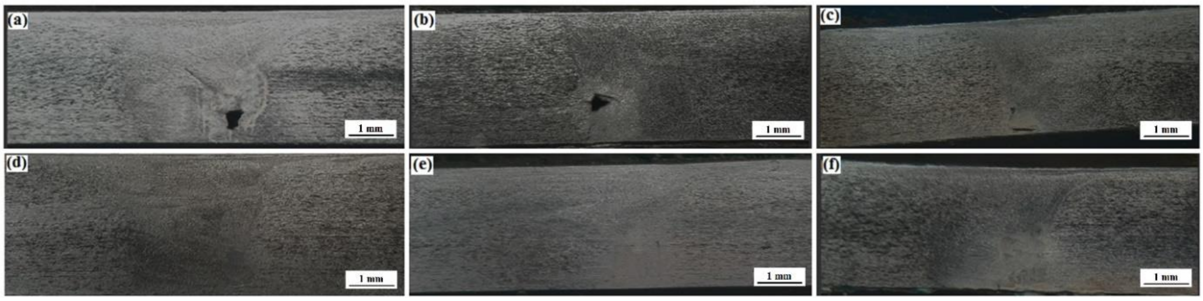

Figure 11. Weld cross-section of (a) CF, (b) CF-Cu, (c) TP-A, (d) TP-B, (e) TP-C and (f) TP-D

According to Figure 11, there are cavity defects at cross sections of CF, CF-Cu, and TP-A welding specimens. The reason for this defect is the lack of proper distribution of heat and plastic flow in the welding section. In the three samples mentioned above, due to the lack of proper plastic flow distribution throughout the weld section and the concentration of the flow in a specific area (RS), cavity defects were created on the other side of the weld. In the other three samples (samples TP-B, TP-C, and TP-D) where there is symmetry in the type of material flow, no specific defect was formed in the weld cross section and the weld was completely free of defects. Another point to be discussed in this Figure is the proper distribution of copper particles throughout the weld. Regardless of the type of welding process (one- or two-pass), tool rotation in the first pass, and movement in the second pass, the copper foil is well distributed in the welding section and the macrograph continuity of the welding section confirms this subject.

3.2 Results of mechanical tests

- *Tensile test*

As mentioned, from each welded specimen, three specimens were extracted for tensile test. In this section, the results of tensile tests have been presented. The output of the tensile test specimens is the force-displacement diagram, which has been transformed into a stress-strain diagram due to the cross-sectional dimensions and the length of the gauge of the tensile test specimen. Figure 12 shows the stress-strain curve of six welded specimens. It should be noted that each of them is reported from the average of three tensile test specimen results.

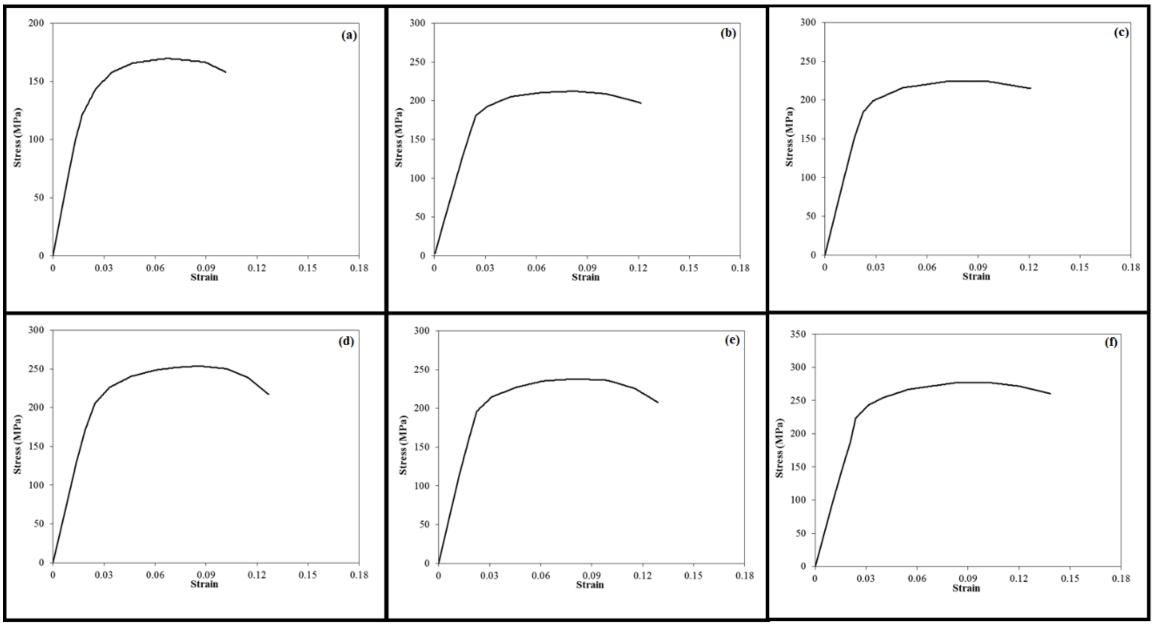

Figure 12. Stress-strain curve of a) CF b) CF-Cu c) TP-A d) TP-B e) TP-C f) TP-D

According to Figure 12 and the results of the tensile test, it was found that the number of welding passes, the presence or absence of copper foil as an interlayer, the number of welding passes, the direction of tool rotation, and the direction of tool movement in the second pass strongly affect the quality. It was observed that by changing the three mentioned parameters, the tensile properties of the welded specimens changed drastically. Based on the results of the tensile test of welded specimens, it was found that the factors determining the ductility and strength of welded specimens are the presence or absence of copper foil, the number of passes used in the welding process, and the linear motion of the tool in the second pass. To better compare the results of strength and ductility of different specimens, in Figures 13 and 14, the graphs of tensile strength bars and the percentage of elongation of the six welded specimens are shown, respectively.

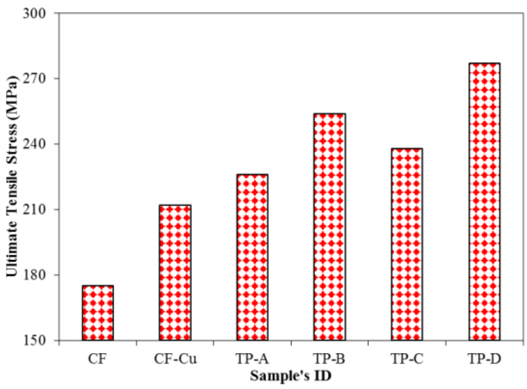

Figure13. Comparison of ultimate tensile strength of different welding specimens

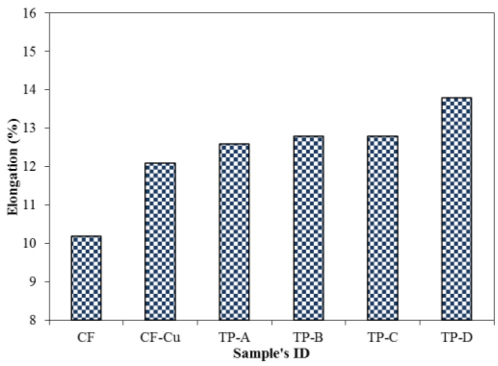

Figure 14. Comparison of elongation percentage of different welding specimens

Based on the bar diagrams presented in Figures 13 and 14, the values of tensile strength and ductility of different welded specimens are significantly dependent on the number of passes used to perform FSW, the presence or absence of copper foil, tool movement direction, and the tool rotation direction in the second pass. It should be noted that when using an interlayer of different material in FSW, the process should be done in such a way that the highest percentage of solubility of the interlayer is in the main material. In the present study, copper interlayer has been used in welding aluminum parts. Welding methods have been used to create the highest solubility of copper in the welding area. In general, if the solubility is low and the copper particles are not well distributed in the weld nugget, the weld efficiency and strength will be greatly reduced. In the present study, an attempt has been made to improve the solubility and distribution of copper particles in the aluminum field by adding another welding pass to the welding process and changes in the direction of rotation and tool movement in the second welding pass. Two parameters for tool rotation and tool movement in the second welding pass change the geometry of the welding nugget and placement of the AS and RS regions in the welding specimen. If the direction of rotation and the direction of tool movement do not change in the second pass, the AS and RS regions coincide in the first and second passes, and practically there is no change in the placement of these areas. However, if the direction of rotation is reversed in the second pass and the direction of linear motion remains constant, the AS and RS regions are reversed in the first and second passes. This creates symmetry in the welding specimen and proper distribution of interlayer particles and causes each side of the workpiece to undergo the AS condition once and the RS position once during the welding process. The same trend applies to welded specimens by changing the direction of the linear motion of the tool. That is, in the TP-C sample, the similar regions are the same, and in the TP-D sample, the AS regions of the first pass coincide with the RS regions of the second pass. According to the results presented in Figures 13 and 14, it was determined that:

a) The addition of copper interlayer to two parts being welded improves the tensile properties (strength and ductility) of the welding specimen due to the creation of an approximate Functional Graded (FG) structure in the weld nugget. This FG structure has common properties of aluminum and copper and hence the mechanical properties of welded specimens are enhanced.

b) Adding another pass to the FSW process increases the strength of the welding specimens. All two-pass welding specimens have higher strength and ductility than one-pass welding specimens. The reason for this is the increase in microstructural changes and the better distribution of the copper

interlayer in the aluminum field, which has occurred due to the repetition of the welding process. In addition to the above, by using two welding passes, some defects created in the first pass are eliminated and the weld created is repaired in terms of defects.
c) The most effective factor in the strength and ductility of welding specimens is the type of two-pass welding technique used and the placement of the AS and RS zones in the first and second passes. If these zones are located dissimilar from each other, a better possibility and solubility conditions in the welding nugget will be formed for the copper interlayer. Under these conditions, the plastic flow created on both sides of the welding line is formed symmetrically and causes the asymmetry of welding zones in the two marginal zones of the welding line to be reduced, which leads to a better distribution of copper particles in the aluminum field and enhancement of the strength and ductility of welding sample.
According to the results presented in Figure 13, the highest tensile strength belongs to the samples TP-D, TP-B, TP-C, TP-A, CF-Cu, and CF, respectively. The mentioned samples have 21, 29, 45, 36, and 58% growth compared to the CF sample, respectively. The highest strength growth is related to the TP-D sample, which has experienced a 58% increase in tensile strength compared to the CF sample. The tensile strength of this sample compared to the base metal is 89.3%.
According to the results presented in Figure 14, the highest ductility belongs to the samples TP-D, TP-B, TP-C, TP-A, CF-Cu, and CF, respectively. The mentioned samples have 18, 23, 25, 24, and 35% growth compared to the CF sample, respectively. The highest growth of ductility is again related to the TP-D sample, which experienced a 35% growth ductility compared to the CF sample. The ductile yield of this sample compared to the base metal is equal to 81.1%.

- *Microhardness test*

As mentioned before, hardness testing of the weld sample sections was performed in this study. Figure 15 shows the micro-hardness distribution of welded specimens by changing the number of passes, the presence or absence of a copper interlayer, the direction of tool rotation, and the direction of tool movement in the second welding pass.

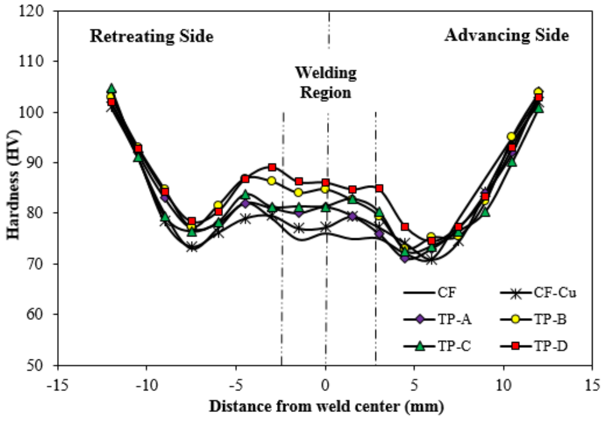

Figure 15. Weld cross-section micro-hardness distribution of welded specimens

One of the mechanical properties of the weld is the distribution of micro-hardness in its cross-section and the study of how the micro-hardness changes at the welding section in terms of changes in welding parameters such as tool changes and rotational and translation speeds leads to a better understanding of material behavior during the welding process. During the FSW process of aluminum alloys, the Stirred Zone (SZ) shows the recrystallized microstructure that in the case of high-alloy aluminum alloys, the presence of high temperatures causes dissolution of sedimentary phases in SZ and partially in Thermo-Mechanically Affected Zone (TMAZ) which is the result of these two factors that determine the hardness of the metal in these zones. There is also some grain growth and ductility in the Heat Affected Zone (HAZ). Since the HAZ connects the base metal to the TMAZ and the TMAZ also connects the HAZ to SZ, eventually the hardness distribution at the junction is W-shaped or V-shaped. Because while eliminating the effects of age hardening and cold work in the nugget zone, the fine-graining of this zone due to recrystallization causes its hardness to increase. Another point about these heat-treating alloys is that the size and dispersion of sediments in these alloys play a greater role in the hardness of these metals than the grain size. Therefore, dissolution and grain growth of these sediments cause a decrease in hardness in the weld zone and their fine-graining and increase in dispersion reduces the hardness compared to the base metal. As can be seen from the micro-hardness distribution diagram for the various states shown in Figure 15, the amount of hardness in the stirred region is reduced for the foil-free state. In samples with foil, due to the presence of copper particles inside the stirred zone and because the hardness of copper is higher than aluminum, a greater hardness is obtained.

3.3 Microstructure of welding specimens

The study of the microstructure pattern of the weld zone and its granulation is known as a factor in studying the distribution of copper particles in the weld nugget and a tool to validate the results of mechanical tests. Therefore, in the present study, microstructure images of the weld nugget of the sample have been investigated. Figure 16 shows the welding nugget of different welded specimens.

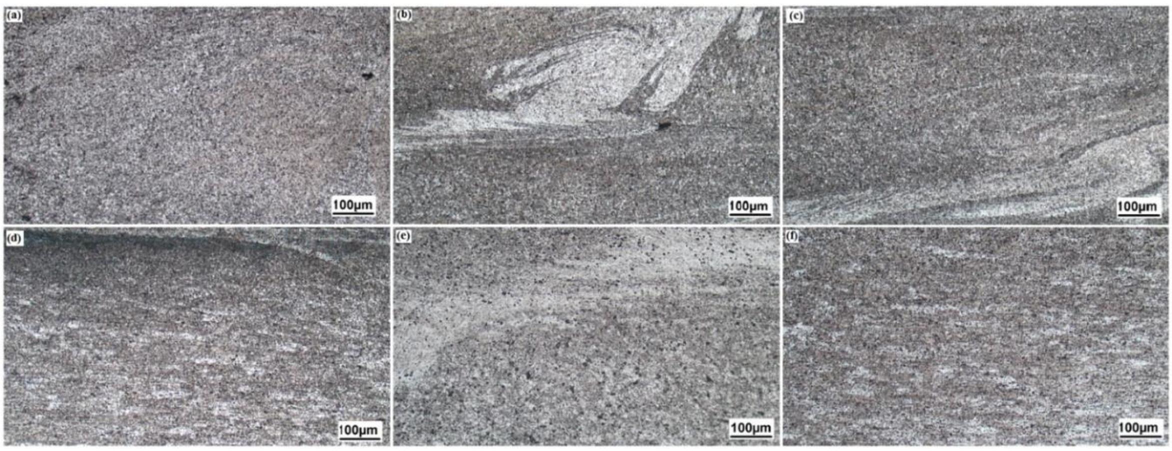

Figure. 16 Weld nugget of a)CF b)CF-Cu c)TP-A d)TP-B e)TP-C f)TP-D

As can be seen in Figure 16, the type of welding technique used (one- or two-pass), the rotating direction and the direction of movement of the tool in the second pass determine how the copper particles are distributed in the aluminum field. According to the results obtained from microstructural images, the best distribution of copper particles in welded specimens belongs to TP-D, TP-B, TP-C, TP-A, and CF-Cu specimens, respectively. For example, as shown in Figure 16(b), it can be seen that the copper particles remain completely in bulk form at the cross-sectional area of the weld, which is highly susceptible to stress concentration during loading. In TP-D and TP-B samples, a suitable distribution of interlayer particles (copper) is formed between the aluminum due to the proper symmetry in the position of the AS and RS zones of the weld during welding. Comparing the results of strength, ductility, and hardness with the distribution of copper particles in the weld nugget, it is concluded that the quality of distribution and dispersion of copper particles in the aluminum phase is directly related to the mechanical properties of welding specimens.

4. Conclusion

In the present study, two methods including common FSW and two-pass FSW have been used to weld AA6061-T6 alloy parts with copper interlayer (200-micron thick copper foil in the area between two welding parts). Tensile test was used to evaluate the mechanical properties and microstructural tests were used to investigate the metallurgical properties of welding specimens. In the continuation, the results of the research have been presented:

- Regardless of the number of welding passes, movement of the tool in the second pass, rotation of the tool in the second pass, and the presence or absence of copper foil, the surfaces of all welding specimens are smooth and the “lack of filling” defect and “cavity” defect are not observed. The only difference between the different welded specimens was the way the material protruded at the edge of the weld.
- It was found that by adding a secondary pass to FSW, the quality of the weld surface is improved and the protrusion defect is less formed in the samples.
- There were cavity defects in the welding section of CF, CF-Cu, and TP-A welding specimens. The reason for this defect in the cross-section of these samples is the lack of proper distribution of heat and plastic flow in the welding section. In the three samples mentioned above, due to the lack of proper plastic flow distribution throughout the weld section and the concentration of flow in a specific area (RS area), cavity defects were created on the other side of the weld.
- According to the results of the tensile test, it was found that the number of welding passes, the presence or absence of copper foil as an interlayer, the number of welding passes, the direction of tool rotation, and the direction of tool movement in the second pass strongly affected the strength and ductility of FSW.
- The addition of copper interlayer to the two workpieces improved the tensile properties (strength and ductility) of the welding specimen.
- Adding another pass to the FSW process (two-pass welding versus one-pass welding) increased the strength of the welding specimens. All two-pass welding specimens had higher strength and ductility than one-pass welded specimens. The reason for this is microstructural changes and the better distribution of the copper interlayer in aluminum, which has occurred due to the repetition of the welding process.
- According to the results, the highest tensile strength belongs to TP-D, TP-B, TP-C, TP-A, CF-Cu and CF, respectively. The mentioned samples have 21, 29, 45, 36, and 58% growth compared to the CF sample, respectively.

- The highest growth of strength was related to the TP-D sample, which experienced a 58% increase in tensile strength compared to the CF sample. The tensile strength of this sample compared to the base metal is 89.3%.
- According to the results, the highest ductility belongs to the samples TP-D, TP-B, TP-C, TP-A, CF-Cu, and CF, respectively. The mentioned samples have 18, 23, 25, 24, and 35% growth compared to the CF sample, respectively.
- The highest ductility growth was related to the TP-D sample, which experienced a 35% ductility growth compared to the CF sample. The ductility increase of this sample compared to the base metal is equal to 81.1%.
- According to the results of micro-hardness distribution, it was found that the value of hardness in the stirred zone decreased for the foil-free specimen. In a specimen with foil, greater hardness is obtained due to the presence of copper particles inside the stirred zone and because the hardness of copper is higher than aluminum.
- According to the micro-hardness profiles, it was found that increasing the number of passes causes an increment in the solubility of copper particles in aluminum and better distribution of these particles in the weld nugget, which ultimately leads to increased micro-hardness in different welding areas. According to the results, the highest and lowest average hardness belong to the samples welded with TP-D and CF, respectively.
- It was observed that the type of welding technique used (one- or two-pass), the direction of the tool in the second pass, and the movement of the tool in the second pass, determine the distribution of copper particles in aluminum. According to the results obtained from microstructural images, the best distribution of copper particles in welded specimens belongs to TP-D, TP-B, TP-C, TP-A, and C-Cu specimens, respectively.

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