Effect of the FSW Tool Pin Profile on Mechanical Properties of the Al6061-Cu Plates Joint

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Abstract

In current research, the Friction Stir Welding (FSW) technique was used to create a metallurgical joint between Al 6061 plates and Cu meat core. The plates were welded using single pass weld with the rotational speed of 1000 rpm and arc travel speed of 30 mm/ min using different tool pin profiles of cylinder, triangle, and hexagonal. After the rolling process and reaching to 1.7 mm of thickness, to evaluate whether there was no separation in layer plates, the radiography test was applied. For more investigation of the created metallurgical bond, optical microscopy (OM) and scanning electron microscopy (SEM) were used. Studies on the welded samples showed a perfect metallurgical bonding. The bonding thickness between Al plates and the Cu meat sample in the samples with pin profiles of triangle, cylinder and hexagonal shape were estimated to be 30, 39 and 45 µm, respectively. Moreover, in comparison to the FSW samples with triangle and cylinder pin profile, the microhardness and ultimate tensile stress were higher in the FSW samples using hexagonal pin profile. It was owing to the fact that hexagonal pin profile had a larger contact area compared with the other two pins. Therefore, the mechanical work using hexagonal pin was more, resulting in an increase in the hardness and tensile stress. In addition, material flow in the bonding zone increased and contributed to an increase in the width of the joint area.

Keywords: Friction Stir Welding, Al 6061, Mechanical Properties

1. Introduction

Friction Stir Welding has been developed since 1991. Processed surfaces using this technique showed improved properties of hardness, tensile stress, fatigue, corrosion and also erosion and wear resistance. On the other hand, soft microstructures with coaxial recrystallized grains improved the super plasticity behavior. Moreover, this process is capable of breaking the large particles and dispersing them homogenously over a lattice. This characteristic contributes to an increase in the material tolerance for deformation and increases the strength [1]. In FSW, the contact of the pin with the surface of the work piece and diffusion in its surface contribute to the generation of heat and due to the friction, the surface of the base metal undergoes plastic deformation. The rotation of the pin causes the materials to transfer from the front to the back of the pin. This severe plastic deformation and the consequent increase in its temperature result in a surface structure of coaxial recrystallized micro grains. Recently, the application of FSW has been reported for producing metallurgical joints with high strength in a variety of materials [2].

The process of producing plates is being researched and developed all over the world using different and designs. In this regard, Monolithic plates comprised of U–Mo alloy based foils encapsulated in aluminum alloy cladding are proposed for conversion of some high performance research reactors to low enriched uranium fuel reactors. Three different fabrication techniques have been considered and evaluated at INL for the fabrication: Hot Isostatic Pressing (HIP), Friction Stir Welding (FSW), and Transient Liquid Phase Bonding (TLPB) [3].

Moore et al. [4] evaluated and compared the process of fabrication of the homogeneous metal plates versus the dispersion aluminum plates. The results of their research showed that FSW technique was applicable for fabrication of metal plates. In addition, an increase in the tensile stress of the created bonding using Friction Stir Welding was observed in comparison to Fusion Welding. During 2007, two of these aluminum plates were exposed to the radiation in Advanced Test Reactor (ATR) in which acceptable results were obtained. Indeed, Moore et al. [4] also investigated the Hot Isostatic Pressing to fabricate metal plates. They concluded that these plates were fabricated with acceptable results when they were subjected to the radiation in ATR. Besides, Lisboa et al. [5] studied on fabrication of aluminum plates with sputtering and transient liquid phase bonding (TLPB) techniques.

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They concluded that for both techniques, sputtering and TLPB applied for co-rolling of UMo alloy, the results are partially acceptable and the fragmentation of the UMo alloy occurs with a total reduction over 45%, with foil thicknesses between 300 and 500 µm. Clark et al. [6] studied the geometry of FSW tools in fabricating planar aluminum plates. The obtained results emphasized using tool pin of bigger diameter instead of tool pin of smaller diameter and utilizing concave tool shoulder instead of convex tool shoulder in order to reach a micro grain joint area with better mechanical properties. To determine the separation status, the ultrasonic test and to determine the minimum thickness of the metal coating of the aluminum plates, ultrasonic and bending tests were applied in the study done by Wight et al. on the planar plates [7]. In the current research, creating joints between plates using rolling contributed to blistering and delamination defects in the aluminum plates in which these defects would be definitely challenging while using. Therefore, the initial plates joining technique is of great importance in order to have a proper metallurgical joint. Keiser et al. [8] applied ultrasonic testing, radiography testing, and microscopic studies using optical and scanning electron microscopies to evaluate the aluminum plates. The results showed separation between aluminum layers in the fabricated aluminum plates using the rolling technique. In this research, 6061 Al plates and Cu were connected to each other using the FSW technique and three pin profiles of triangle, cylinder and hexagonal and then after the rolling process evaluated from the strength, hardness and microstructure point of view.

2. Materials and Methods

In the current study, 6061 rolled aluminum plates with the thickness of 2.9 mm were used as the side plates of the planar plates. The plate's dimensions were considered as 150 mm×130 mm. On the other 6061 Al plate of 5.8 mm thickness, a notch of 57.8 mm× 87.6 mm was made in order to place the Cu meat in it. The mechanical properties of the Al plates are given in Table. 1.

Table. 1 6061 Al mechanical properties [UNS A96061; ISO AlMg1SiCu].

Elongation (%)	Tensile stress (Mpa)	Yield stress (Mpa)	Status	Material
12	310	276	Rolled	6061 Al

In order to put FSW into practice, three 6061 Al plates with the aforementioned dimensions were prepared. On one of these plates, a notch of proper dimension of the Cu meat was made and after placing the Cu meat in the prepared notch, two other Al plates placed on both sides of the notched sample.

Fig.1 shows the applied plates in the current study.

Fig. 1. Al plates and Cu samples.

In order to conduct the friction stir process, a modified vertical milling machine was applied. In this research, pin profiles of triangle, cylinder and hexagonal fabricated of the H13 hot work tool steel with the 54 RC hardness as given in Table. 2. Were used. The geometry of the pins has been chosen according to the previous studies [8]. Their profiles are shown in Fig. 2.

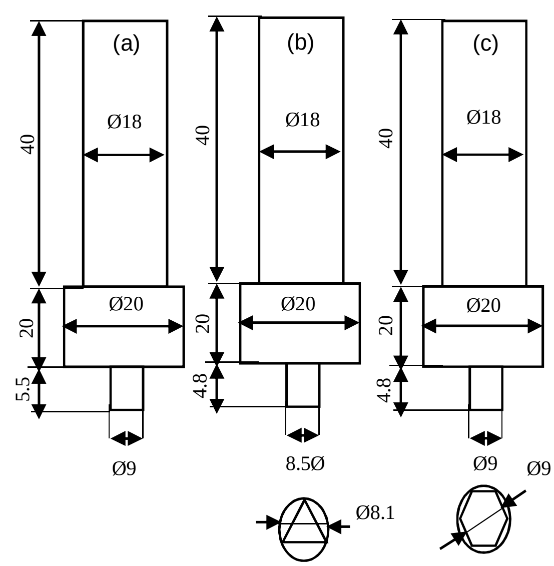

Fig. 2.Pin profile of a) cylinder b) triangle C) hexagonal used in FSW.

Table. 2. Al 6061 plates samples specification.

Pin dimensional specification	Tool pin profile	Sample code	Number
In circle diameter of 8.1 mm	Triangle	F1	1
Cylinder with diameter of 9 mm and concave shoulder	Cylinder	F2	2
In circle diameter of 9 mm	Hexagonal	F3	3

Single pass FSW on F1 to F3 samples was conducted using rotational speed and welding speed of 1000 rpm and 30 mm/min, respectively. The depth of tool shoulder in the work piece was considered 0.3 mm. The procedure of conducting FSW process is shown in Fig. 3.

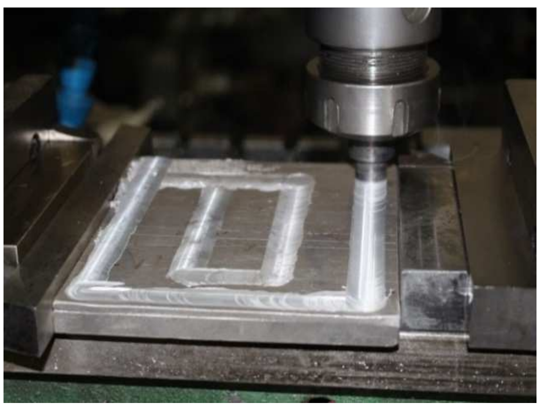

Fig. 3. FSW of the planar Al 6061 plates.

For a better contact of the tool shoulder with the surface of the plate and a proper flow of the materials during the process, the slope of 2 degrees (the angle between tool vertical axis and the horizontal axis of the samples) was chosen. After the FSW process, the samples were exposed to the rolling process. Rolling was done to decrease the thickness of the samples to the reactor standard thickness. Six stages of rolling were performed on the samples with one stage of cold rolling and five stages of hot rolling. To check the joint quality in the FSW process, radiography test was used the parameters of which are given in Table. 3.

Table. 3. Radiography parameters and specification.

Source Type	mA	KV
X-ray	10	250

In order to survey the welded platelayers separation, Philips optical microscope and Philips XL30 scanning electron microscope were used. Therefore, to prepare the required samples, cross sectional samples were chosen from specified sections in Fig. 4. Then these samples were prepared and in order to make the microstructure visible, 5 g of $FeCl_3$, 2 ml of HCl and 95 cc of C_2H_5OH were used as the etchant. In addition, the width of the joint area of the samples was analyzed using IMAGE J software. For tensile testing, a tension device (INSTON-4486 30-ton) according to ASTM E8 standard and strain speed of 10 mm/min was applied. Vickers microhardness test was performed on the samples using Shimadzu M micro-tester according to ASTM E140 standard. The applied load and the loading time were set 50 g and 15 sec, respectively.

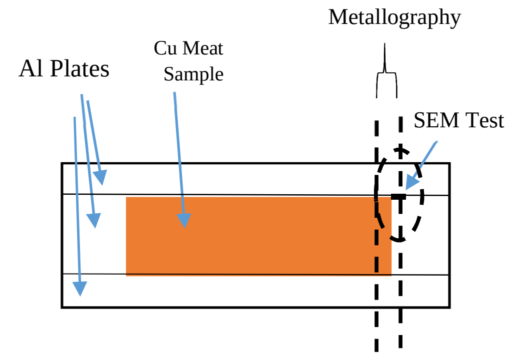

Fig. 4. Schematic of the zones used for OM and SEM images.

3. Results and Discussion

3.1. Radiography Test

For revealing the internal defects, a radiography inspection is conducted. As can be seen in Fig. 5, the radiography results show a proper Joining. In addition, no boundary layer separation was observed after FSW and rolling processes.

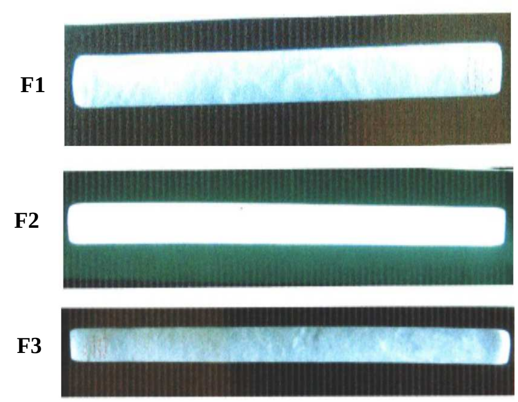

Fig. 5. Radiography images of the different samples.

3.2. Microstructure

Metallography images of sample F1 has been shown in Fig. 6. The images were taken after the FSW and rolling processes. Fig. 6(a) shows the bonding zone of Al plates layers. In the image, a perfect bonding was observed at the magnitude of 50-µm. The thickness of the bonded layer was estimated at 30 µm. The metallography images of sample F2 are shown in Fig.7. as it is illustrated, there is a good joint of bonded Al layers. The width of bonding between Al plates and Cu core has been estimated to be 30 µm. in Fig. 8. a quite favorable joining between Cu core and Al plates in sample F3 is being seen. The minimum bonding width between Al plates and Cu core has been estimated at 45 µm. Therefore, the width of the bonded zone of sample F3 increased by 33% and 13 % compared with sample F1 and sample F2, respectively. This increase in the width of the bonded zone stemmed from the hexagonal pin due to its bigger contact surface in comparison to the other two pins. Therefore, the mechanical work applied on the sample using this pin (Hexagonal pin) is more and the material flow in the bonded zone was increased and contributed to an increase in the width of the joint zone.

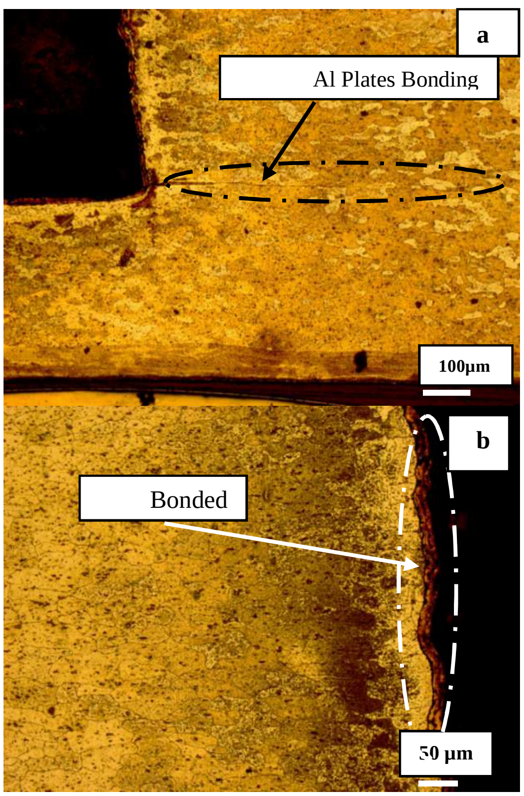

Fig. 6. OM micrograph of the Sample F1 a) Al plates bonding zone b) 6061 Al plates and Cu core bonding zone.

on the other hand, an increase in the contact area of the tool pin caused friction production and consequently there was a rise in input heat that caused a wider bonded zone [8-9]. Fig. 9 shows the SEM images (Imaging backscattered electrons) of the marked zones in Fig. 4. a quite favorable bonding can be seen in this image.

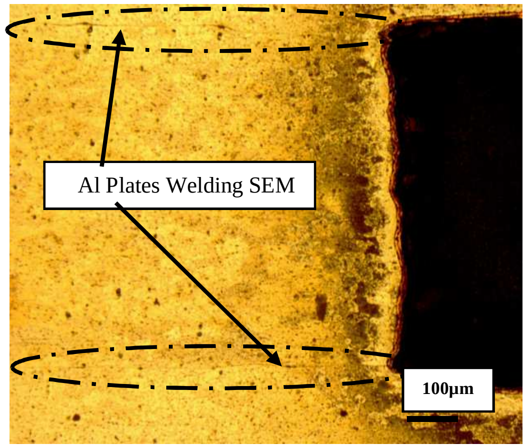

Fig. 7. OM micrograph of the sample F2.

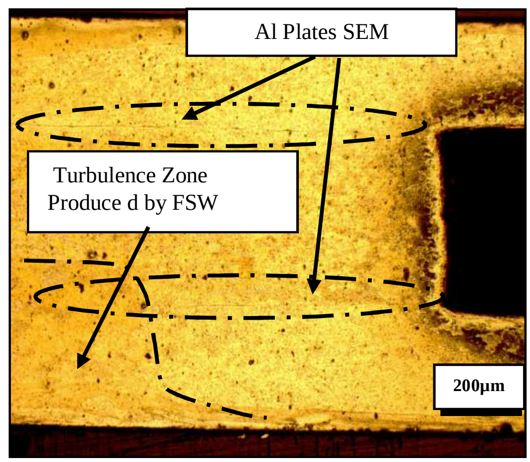

Fig. 8. OM micrograph of the sample F3.

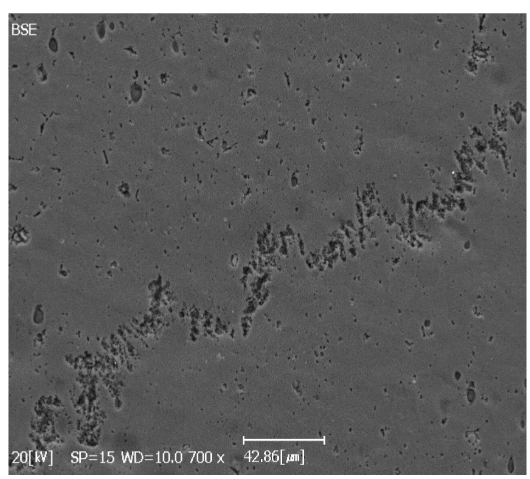

Fig. 9. SEM micrograph of the Al plates bonding zone.

3.3. Tensile Test

The results of tensile test for samples F1, F2 and F3 denoted in Table 4. As can be determined from Table 4. the tensile stress of sample F1 is about 9 % less than 6061 Al alloy. Samples F2 and F3 tensile strength were obtained to be 325 and 324 MPa respectively and had a 4% increase compared with the base metal.

The difference in the tensile stress of sample F1 was about 13 % in comparison with sample F2 and sample F3, which shows an increase in the tensile stress of samples F2 and F3 owing to the use of cylinder and hexagonal pin compared to the triangle one. An increase in the tensile stress using hexagonal pins was because of the contact area increasing in the pin, which contributed to an increase in the width of the bonding zone. Therefore, the joints have been stronger. In addition, the amount of mechanical work increased and by reduction in the grain size due to the dynamic recrystallization, the tensile stress would be increased [8-10].

Table. 4. The tensile stress results of different samples.

Elongation (%)	Yield Stress (Mpa)	Tensile Stress (Mpa)	Sample code
9	198	280.6	F1
15.7	254	325	F2
19.4	269.5	324	F3

3.4. Microhardness Test

The results of microhardness test are presented in Fig. 10. This test has been performed from cross sectional zones and the joint boundary of Cu core and aluminum plates considering Fig. 11. As can be seen, the microhardness on the surface of the samples is high in comparison to the depth of the samples. It is because of the FSW process and the produced work hardening on the surface of the samples. The microhardness in sample F1 is much less than samples F2 and F3. On the other hand, hardness increment using hexagonal pin could be justified in a way that with an increase in the contact surface of the pin, the input heat increased. So, the precipitations dissolved and due to more mechanical work which is due to the geometry of the pin type, as the grains become finer, the participates in the bonding zone got finer and had a better distribution which caused an increase in the hardness [9-12]. Therefore, the results of microhardness test of the samples indicate that conducting the FSW process in welding the plates using hexagonal tool pin compared to triangle and cylinder tool pins had a more favorable result.

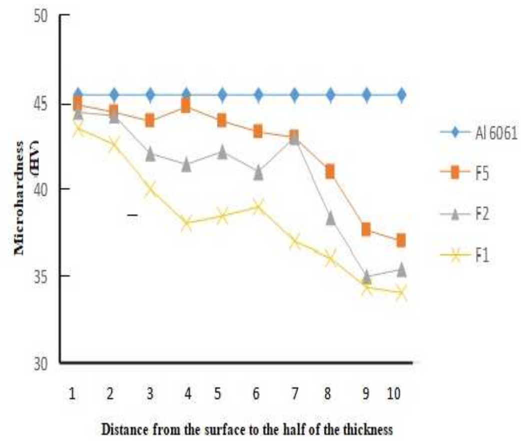

Fig. 10. The results of microhardness test of different samples.

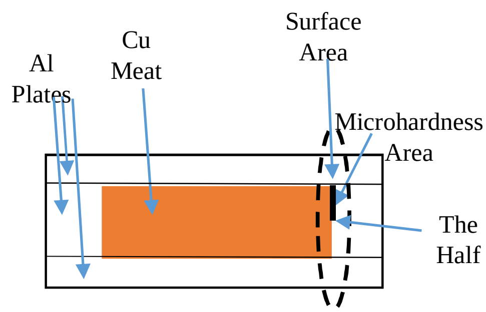

Fig. 11. The schematic of the areas, which the microhardness test was done.

4. Conclusions

1. The radiography test indicated that samples F1, F2 and F3 were defects free and no separation line was observed.
2. The metallography and SEM results of the fabricated aluminum plates showed the possibility of creating a bonded layer with a proper width using FSW technique in aluminum plates with three types of tool pins and the width of the bonded area using hexagonal pin got the largest area.
3. The microhardness and tensile stress in the joint sample using hexagonal pin increased in comparison to the welded samples using cylinder and triangle pins. It was owing to the larger contact surface in the hexagonal pin in which contributed to more mechanical work and consequently dynamic recrystallization so the grains got finer and the hardness and strength increased.

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