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GRADUATE RESEARCH ARTICLE

Mechanical Properties and Microstructure of Dissimilar Friction Stir Welding of Pure Aluminum to Low Carbon Steel

Mohamed Mohamed Abd Elnabi[1*], T. A. Osman[1], A. E. El Mokadem[1], A. B. Elshalakany[2]

[1] Mechanical Design and Production Engineering Department, Faculty of Engineering, Cairo University, Giza, Egypt

[2] Production Engineering and Printing Technology Department, Engineering Department, Akhbar El Yom Academy, 6th of October City, Egypt

*Corresponding Author email: abdelneby_dx@hotmail.com

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Student(s)

- Mohamed M. Abd Elnabi

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Mentor(s)
- T. A. Osman
- A. E. El Mokadem
- A. B. Elshalakany

ABSTRACT

The purpose of this research is to use friction stir welding (FSW) to join dissimilar metals, annealed low carbon steel and A1050 pure aluminum. A butt joint with a similar sheet thickness of 1.9 mm was applied. The novelties of the research are relatively using high generated heat produced by a combination of low traverse speed and high rotational speed to perform the dissimilar joints and using a tool material (K107cold work tool steel) which has not been used in FSW with tool cooling. The present work studied the effect of FSW variables such as tilt angle, tool cooling, base metal location on mechanical properties. Tensile tests were used to evaluate the mechanical properties of the dissimilar joints. The microstructure specimens were examined using a scanning electron microscope (SEM). Sound dissimilar joints were successfully produced. The maximum joint efficiency obtained in this study is 51.7% of the aluminum tensile strength. The microstructure images showed that many steel fragments were sheared off from the steel surface by the tool action and scattered in the weld nugget, a continuous intermetallic compound (IMC) layer formed at the interface, the thickness of the IMC layer at the interface decreased in the thickness direction of the weld. $FeAl_3$ IMC phase was only observed at the interface.

Keywords: Friction stir welding; Tool Steel; Tilt angle; Intermetallic compound; Dissimilar metals; Tensile Strength

1 Introduction

Nowadays, fuel consumption savings of vehicles is one of the important issues for us to resolve. This savings helps to reduce the environmental pollution. Lessening the weight of the vehicle is the way to reduce the fuel consumption. The most materials used in the vehicle industry are steel materials. The steel materials which are relatively heavy increase the vehicle weight. Many ways can be used to reduce the vehicle weight. Some of these ways are joining of steel materials with different thicknesses [1], replacing some components made of steel with lightweight metals such as aluminum, joining of lightweight metals especially aluminum and aluminum alloys (very costly), and joining of the both (steel and aluminum) that helps to reduce the cost and the weight problems. Many studies successfully have been welded similar or dissimilar aluminum metals without showing fusion defects by friction stir welding (FSW) [2-6]. Joining of aluminum to steel is very difficult by fusion welding techniques due to many reasons such as a huge difference in the melting temperature (aluminum 650 ^{O}C, steel 1538 ^{O}C) and in the coefficient of thermal expansion and thermal conductivity, poor wettability of the aluminum on the steel surface, and a little solubility of Fe in Al. A dissolved iron in aluminum produces brittle intermetallic compounds (IMCs). These IMCs destroy mechanical properties of the joint [7]. According to Al-Fe phase diagrams, there are many IMCs may be formed during the process such as Fe_2Al_5, $FeAl_3$ and $FeAl_2$ [8]. To overcome these welding problems, it should weld this joint without melting. There are solid state welding processes which join similar or dissimilar metals without melting such as friction welding [9], ultrasonic joining [10], FSW [11-22]. FSW was invented and patented by The Welding Institute (TWI) in1991 [23]. The FSW was only applied in this study to investigate the dissimilar joint. The mechanism of the FSW is thermo-mechanical which needs three elements to complete the operation. These elements are heat generation, plastic deformation, and forging. The heat is generated by the friction between a rotated tool and a base metal, and the heated base metal becomes very soft (plastic deformation state). The tool of the FSW consists of a shoulder which helps to force the plasticized metal and a pin to stir this metal from side to side to make a joint. Few studies were investigated the welding of aluminum to steel by FSW [11-22]. M. Dehghani *et al.* [11] welded mild steel to AA3003-H18. They examined the effects of process variables on the mechanical properties. The maximum tensile strength which they achieved was 140 MPa (about 73% of Al base metal) under the variables condition of 12 mm/min traverse speed and 450 rpm rotational speed. They also reported that Al_5Fe_2 and Al_6 (Fe, Mn) IMC phases were observed at the interface and in the nugget, respectively. K.Kimapong *et al.* [12] welded SS400 mild steel to AA5083. They studied the effects of pin diameter, weld location, tool offset, and rotational speed. They reported that the pin diameter had a slight effect on the tensile strength, and the tensile strength increased with decreasing the rotational speed from 1250 to 250 rpm. There was no bonding between the metals when the steel was placed on the retreating side. They also reported that the high-speed tool steel could not withstand the frictional heat when the tool offset increased toward to the steel side (C. M. Chen *et al.* [14, 24] reported the same result of the tool offset effect but with W302 tool steel). They observed FeAl and $FeAl_3$ phases at the interface on the steel side and the aluminum side, respectively. Xun Lin *et al.* [13] welded 780/800 trip steel to AA6062-T651. They investigated the effects of process variables on the joint strength and the formation of IMCs. They mentioned that the thickness of the IMCs decreased with decreasing the welding speed and with decreasing the tool offset toward to the steel side, and the joint efficiency was destroyed when the thick IMCs formed at the interface. Alireza *et al.* [15] obtained the best result when using a combination of welding speeds lead to generate low heat input (280 rpm and 160 mm/min). M. Habibnia *et al.* [16] (AA5050 to 304SS) and Hamed *et al.* [17] (AA50052 to AISI 304) mentioned that the FSW defects appeared when the tool offset to steel side was approximately high up to 1.6 to 2 mm. Hamed *et al.* [17] and Zakaria *et al.* [18] (AA6061-T6 to Low carbon steel) reported that the strength of the joint increased with increasing the traverse speed. Shuhuai *et al.* [19] obtained the best strength at the formation of thin IMC at the interface (less than 1 µm). Masoumen *et al.* [20], Long *et al.* [21] and Z. shen [22] used a lap configuration to join aluminum to steel. These studies circled the effect of the formation of IMC and studied the effect of this on the quality of the joint. Most studies have been tried to use a wide combination of welding speeds to reduce the heat input which decreases the thickness of IMC and to preserve the tool geometry. The generated heat according to this concept cannot strongly influence the steel side.The novelty of the research is relatively using high generated heat by using a combination of a low traverse speed and a high rotational speed to perform the dissimilar joints. The aims of the present work are to weld dissimilar joints between low carbon steel and commercial pure aluminum, to investigate the effects of FSW variables on mechanical properties and microstructure of the joints.

2 Experimental Procedures

2.1 Materials

2.1.1 Base Metals

The base metals used to perform the dissimilar joints are pure aluminum (A1050) and annealed low carbon steel with a similar sheet thickness of 1.9 mm. The chemical composition of the base metals used is given in Table 1. Mechanical properties of the base metals, including ultimate tensile strength, yield strength, elongation, failure stress and Young's modulus, are given in Table 2.

Table 1: *Chemical compositions of the base metals used*

Material	Chemical composition (wt. %)									
Pure aluminum A1050	**Si**	**Mn**	**Zn**	**V**	**Fe**	**Mg**	**Ti**	**Cu**	**Al**	**-**
	0.15	0.001	0.013	0.037	0.03	0.015	0.009	0.1	99.7	-
Low carbon steel	**Si**	**Mn**	**Cr**	**Mo**	**Ni**	**V**	**P**	**S**	**C**	**Fe**
	0.01	0.28	0.05	0.004	0.01	0.002	0.015	0.007	0.076	remainder

Table 2: *Mechanical properties of the base metals used*

Material	Ultimate Tensile Strength MPa	Yield Strength MPa	Elongation %	Young's Modulus GPa	Failure Stress MPa
Low Carbon Steel	310	200	47	146	210
Aluminum 1050	144	116	2	69	60

2.1.2 Tool Metals

A Simple FSW tool was used with a flat shoulder and a cylindrical pin. Each experiment was welded by a new tool. The dimensions of the tool are 18 mm shoulder diameter, 6 mm pin diameter, and 1.6 mm pin length. The tools were made of W302 hot work tool steel and K107 cold work tool steel (BÖHLER standard). The tools were hardened by heat treatment according to the BÖHLER standard [25]. The chemical composition and the heat treatment cycle of the both K107 and W302 are shown in Tables 3 and 4, respectively.

Table 3: *Chemical composition of the tool materials*

Chemical composition (wt .%)	C	Si	Mn	Cr	Mo	Ni	V	W	Fe
W302	0.35	0.97	0.35	4.92	1.30	0.33	0.89	-	remainder
K107	2.10	0.25	0.34	11.04	0.034	0.16	0.022	0.68	

Table 4: *Heat treatment cycle of the tool materials*

Treatment cycle	Hot work tool steel (W302)	Cold work tool steel (K107)
Hardening cycle		
Hardening temperature	1050 ^{O}C	950 ^{O}C
Raising time to the hardening temperature	~5.30 hr	~ 5 hr
Holding time at the hardening temperature	30 min	
Quenching (cooling)	In oil	
Tempering cycle (immediately after hardening)		
Tempering temperature	500 ^{O}C	
Tempering time	3 hr	
Cooling	In air	
Hardness	50 - 53 HRC	55- 58 HRC

2.2 Friction Stir Welding Procedures

The experimental joints were carried out by a WMW ECKERT vertical milling machine. A butt joint form was used. The direction of the experimental weld line is perpendicular to the rolling orientation of the sheets. The base metals were clamped and supported by a steel backing plate. The lengths of the weld were 8, 12 and 16 cm and the tool materials used were K107, W302 tool steel. These conditions were used to evaluate the ability of the tool materials to withstand heat and friction. Table 5 illustrates the values of the process variables of the experimental joints. The steel was placed on the advancing side, and the aluminum was placed on the opposite side (retreating side) in all the joints except one joint (joint 4, the steel was placed on the retreating side). A traditional type of tool cooling (by a cooling hose from outside) was applied to cool the tool, and the coolant dropped from the tool relatively cooled the weld zones. The experimental procedures and the place of the samples test of 8, 12, and 16 cm welds are given in Figure 1. The other process variables were fixed in all experimental joints: 1550 rpm rotational speed, 17 mm/min traverse speed, 0.5 mm pin offset to the steel side (0 mm offset: the pin was completely plunged in the aluminum side), 1.6 mm pin length, and 0.2 mm plunge depth. Photographs of the weld face and the weld root of the welded joints are presented in Figure A.1 (Appendix A). These values of the process parameters were obtained after many trials. During the screening of the process parameters, many surface defects were observed as shown in Figure A.2 (Appendix A). These defects relate to low generated frictional heat, high tool offset to the steel side or insufficient flow of the deformed metal.

Table 5: *Experimental variables condition*

Run	Tilt angle ^{O}	Tool cooling	Weld length cm	Tool material
1	1	without	8	K107
2	1	without	8	K107
3	1	without	16	K107
4*	1	without	16	K107
5	1	with	8	K107
6	1	with	16	K107
7	1.5	without	12	W302
8	2	with	12	W302

*Steel is placed on retreating side/ aluminum on advancing side

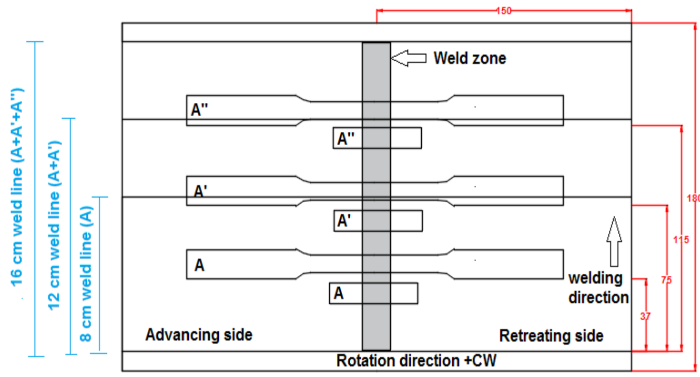

Figure 1: *Experimental procedures and samples test (8 cm weld: only A sample, 12 cm weld: both samples A and A', 16 cm weld: All samples A+A'+A'')*

2.3 The Analysis of Specimens

2.3.1 Tensile Test

Transverse tensile specimens were used to evaluate the strength of the dissimilar joints. The transverse direction is perpendicular to the welding direction. The tensile specimens were cut by a water jet machine according to ASTM E-8M standard [26]. The specifications of the tensile specimen are shown in Figure 2. A GT-7001 hydraulic universal testing machine was used to do the tensile test. The test was performed at 4 mm/min crosshead speed.

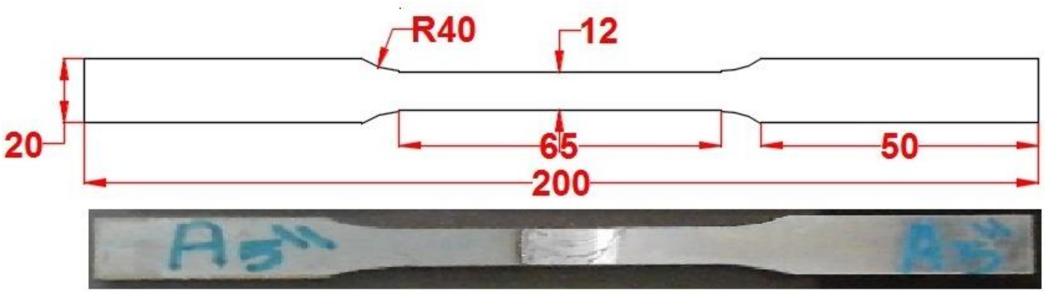

Figure 2: *Tensile test specimen*

2.3.2 Metallography Examination

The specimens were taken from a welded section included both the weld zones of the joint (transverse direction of the weld). The metallography examination was examined by using a scanning electron microscopy (SEM). Then, the specimens were analyzed by using an energy-dispersive spectroscopy (EDS) to know the elements or chemical characterization of selective regions such as particles or intermixing interfaces. By using the weight or atomic percentage of each element (Al/Fe) of these interfaces, it can predict the intermetallic phases formed. To ensure these results, x-ray diffraction (XRD) was used for phase identification on the entire weld zone.

3 Results and Discussion

3.1 Effects of Process Parameters on Joint Ultimate Tensile Strength (UTS) and Ductility

The stress-strain curves of the base metals and the dissimilar joints are given in Figure 3. Table 6 shows the mechanical properties of all the experimental joints. Without controlling the tool wear and the forces applied to the tool during the process, the joints may be destroyed. It might not obtain the same results without controlling the previous problems. This process (Aluminum/ Steel) is very difficult and expensive to optimize under these process conditions. This process needs advanced tool materials to withstand the frictional heat and needs an FSW machine (not milling machine) to control the forces during the process. Based on the available results, the effect of the process parameters is discussed.

Table 6: *Mechanical properties of the welded joints*

J	Tilt angle	Tool cooling	Weld length (cm)	Tool material	Results						
					S1 *	**S2**	**Tensile Strength MPa**	**Yield Strength MPa**	**Ductility %**	**Fracture location**	**Tool wear ****
1	1	without	8	K107	1	5	79.2	53.3	6	Nugget	+
2	1	without	8	K107	2		48.4	33.5	3	Nugget	+
3	1	without	16	K107	1		54.3	36.5	4	Nugget	+++
					2		12.6	-	0.5	Interface	
					3		-	-	-	-	
4#	1	without	16	K107	1	3	~4	-	0	Interface	+
					2		~0	-	0	-	
					3		~0	-	0	-	
5	1	with	8	K107	1	4	75.8	51.5	5	Nugget	No
6	1	with	16	K107	1		71.6	48.8	4	Nugget	+
					2		22.7	20	1	Interface	
					3		20.6	19	1	Interface	
7	1.5	without	12	W302	1	2	77	58	6	TMAZ	++
					2		36	25	3	Interface	
8	2	with	12	W302	1	2	74.5	50.9	6	Nugget	++
					2		40	31.2	4	Nugget	

\# Steel was placed on the retreating side.
*A number of specimens of each run (S1) and each experimental condition (S2).
**+ Normal wear (10-20%), ++ medium wear (50-60%), +++ high wear (90-100%).

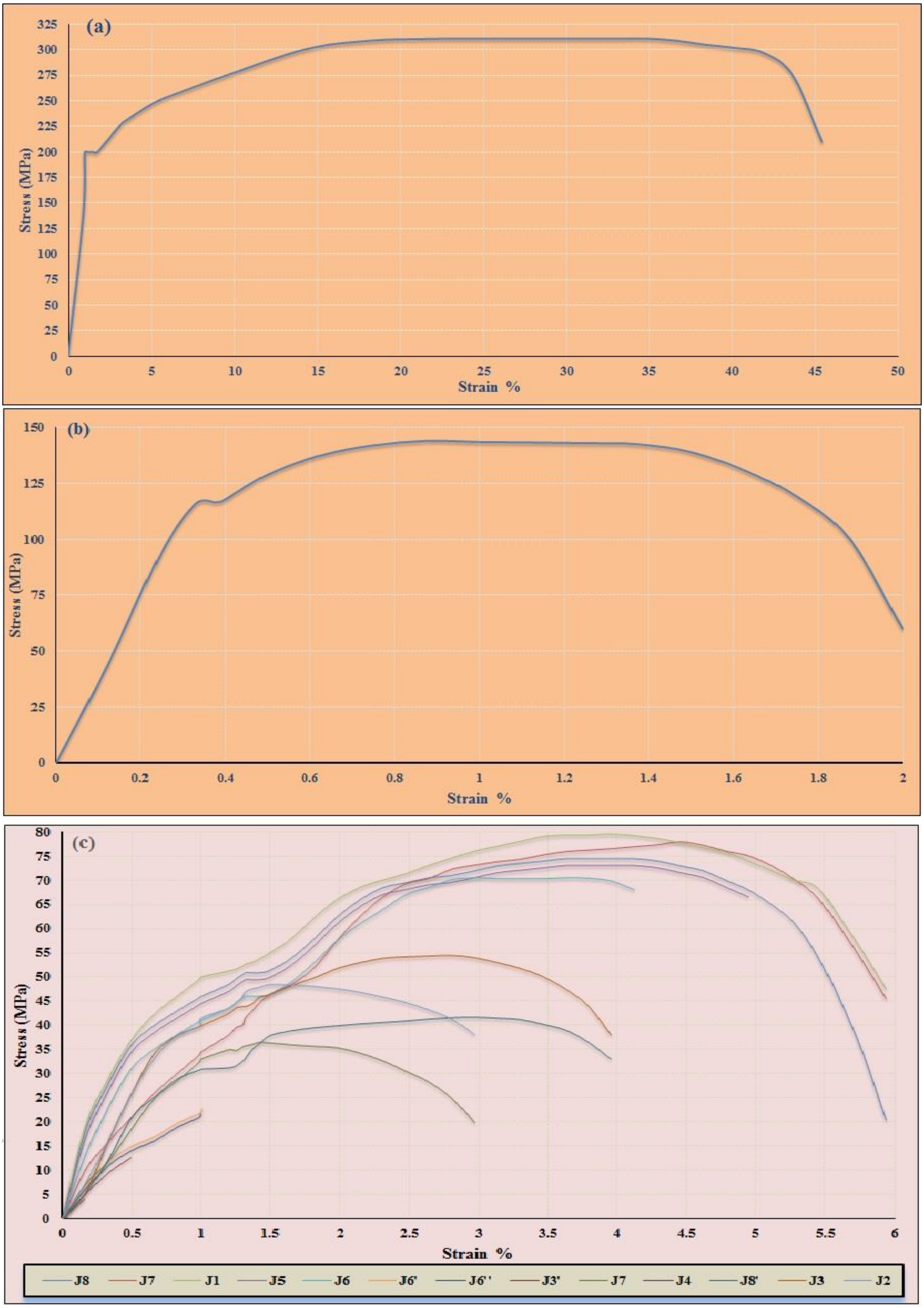

Figure 3: *Stress-strain curve of the base metals and its joints:*
(a) annealed low carbon steel, (b) A1050 pure aluminum, and (c) dissimilar joints

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Figure 4a; b illustrates the difference in the UTS with 1°,1.5° and 2° tilt angles and with/without tool cooling. It is obvious from this figure that the UTS minimally decreased with increasing the tilt angle under all the variable conditions. The UTS decreased from 60.63 MPa at 1° tilt angle to 56.6 MPa at 1.5° tilt angle and from 73.7 MPa at 1° tilt angle to 57.25 MPa at 2° tilt angle. The objective of the tilt angle is to increase the pressure on the trailing edge of the tool which helps to force the plasticized material correctly. Ram D.

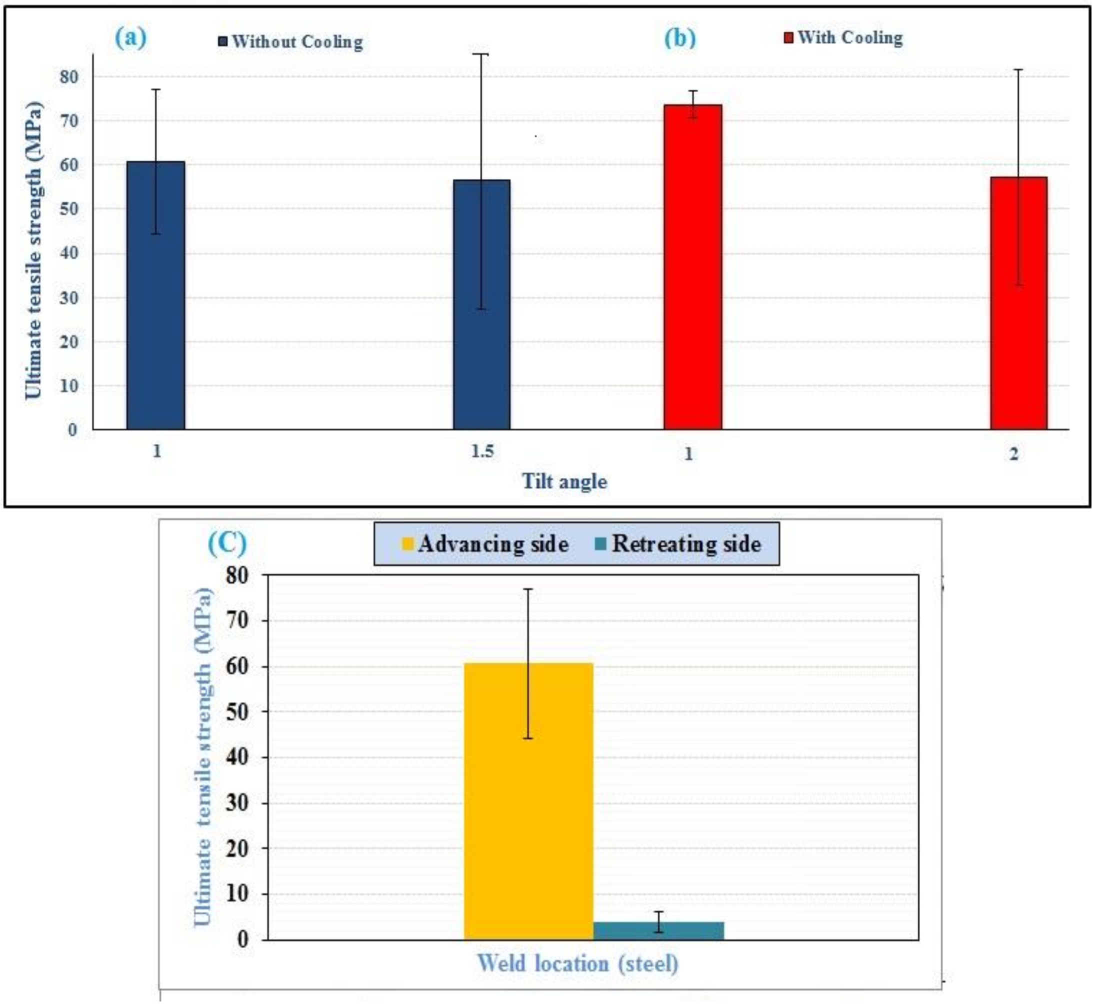

Figure 4: *Effect of process parameters on UTS: (a) effect of tilt angle without tool cooling; (b) effect of tilt angle with tool cooling; (c) effect of weld location*

Shinde [27] reported that the tilt angle affected the vertical and horizontal flow of the weld material. The tensile strength of the welds increased when tilt angle was changed from 0° to 2°. C. Meran *et al.* [28] reported that the angle of 0° caused a serious problem in the weld areas. Small increment on the tilt angle to 2° helped to increase the joint strength. The obtained results disagree with these points and the highest UTS achieved is 73.7 MPa at 1° tilt angle. The high tool tilt angle inserted on the surface of the metals especially on the steel side increases the shearing off big steel fragments that devastate the aluminum nugget. The UTS increased by using the tool cooling (with partial cooling of weld zones). The UTS increased from 60.63 MPa without cooling to 73.7 MPa with cooling at the same variables condition. The tool cooling with partial cooling of weld zones minimized the heat in the weld zones. M. Dehghani *et al.* [11], Xun Lin *et al.* [13] and H. Springer *et al.* [29] indicated that the joint strength decreased with increasing the heat in weld zones due to the formation of thick IMCs.

The pin rotation direction was reversed compared to the previously mentioned welds. With a counterclockwise pin rotation direction, the aluminum was located on the advancing side of the joint (joint 4). It appears from this view that welding was achieved but with a small crack at the center of the weld.

K.Kimapong *et al.* [12] reported that there is no bonding between both sides (Al-St) when the steel was placed on the retreating side due to the non-activation of the steel side. Approximately the same result is obtained in this study. When the location of the steel was changed from the advancing side to the retreating side, the UTS extremely decreased from 60.63 to 4 MPa as shown in Figure 4c.

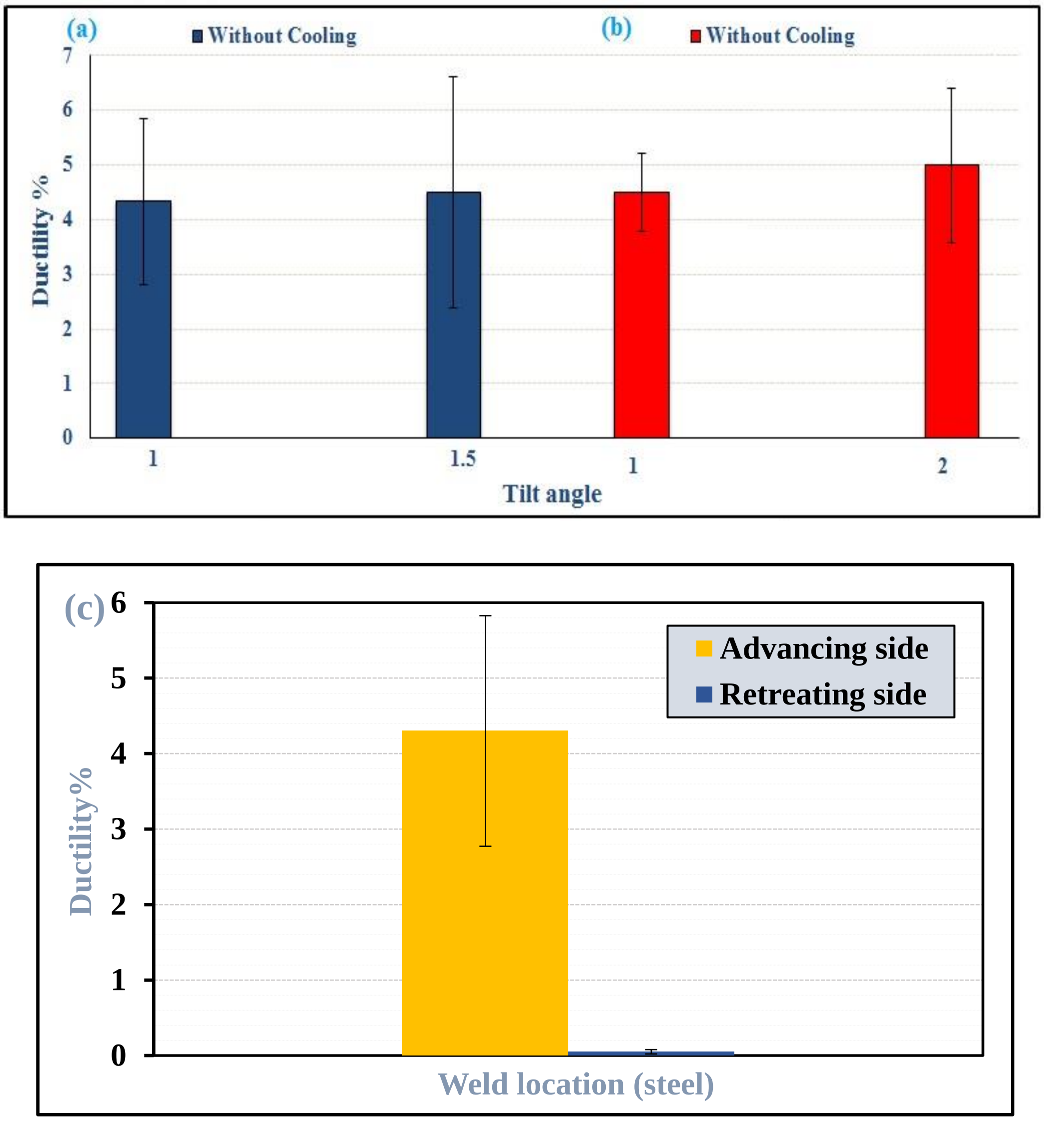

Figure 5: *Effect of process parameters on ductility:*
(a) effect of tilt angle without tool cooling; (b) effect of tilt angle with tool cooling; (c) effect of weld location

Most of the elongation of the specimens happened at the aluminum side, mainly on the weld zones. Throughout the welding process, the aluminum side was mainly affected by the frictional heat that assisted to dissipate the effect of the strain hardening of the aluminum. As a result of this, the weld zones returned to an annealed condition. This loss served to increase the ductility of the joint. The average elongation of the joints is between 4.3 % to 5 % that is higher than the elongation of the aluminum base metal (2 %). Figure 5a; b represents the effect of the tilt angle and with/without tool cooling on the ductility of the dissimilar joint. It is clear that the ductility of the joints increases with increasing the tilt angle from 1^{O} to 1.5^{O} without tool cooling and from 1.5^{O} to 2^{O} with tool cooling. As mentioned before, when the steel was placed on the retreating side, the intermixing between both the sides did not occur. By this condition, the specimens of this joint rapidly failed during machining or during the tensile test. This explains why the ductility at this condition approximately is near to zero. Figure 5c illustrates this effect.

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3.2 Metallographic Analysis

Figure 6 shows SEM image of the nugget on the Aluminum side of the best joint (taken from the top view of the nugget). The aluminum nugget was filled with steel fragments with different sizes. There are many large steel fragments sheared off from steel edge and distributed in the aluminum nugget due to the movement of the tool in the traverse direction. These pieces produce large IMCs which decrease the tensile strength. Figure 7 shows enlarged SEM image of one of those fragments. Around the steel fragment, the IMC layers formed with different thicknesses. The XRD spectrum of the joint (in weld zone) represents the existence of $Al_{13}Fe_4$ $FeAl_3$ and FeAl intermetallic phases in the weld zone as shown in Figure 8. FeAl also was found in the weld zone of Al/ St FSW as reported by Xun Lin *et al* [13] and H.Springer *et al* [29], respectively. FeAl and $FeAl_3$ were found in the weld zone of Al/ St FSW as reported by Kimapong *et al* [12], Shuhuai *et al.*[19] and Masoumen *et al.* [20]. The intermetallic compound at the Al/Fe interface is identified as $FeAl_3$ based on EDS result. The XRD results confirmed the existence of this phase in the microstructure of the weld. Figure 9 shows SEM image taken from the top view at the interface in two different zones and its EDS analysis. The thicknesses of the IMC formed at the interface are 3 µm and 7.5 µm in the zone 1 and zone 2, respectively. Also, from EDS results, according to Al/Fe phase diagram [8], it can know the phases formed at the interface by the weight or atomic percentage of each element (Al/Fe). The IMC phase formed at the interface on both the zones is $FeAl_3$. There are two different observations at the interface in the same joint that explain why the strength of the joints decreases. In zone 1, the IMC layer continuously formed at the interface with the same thickness. But in zone 2, the IMC layer continuously formed at the interface with different thicknesses and with many cracks. The cracks may be formed due to the absence of controlling the forces and vibrations during the operation.

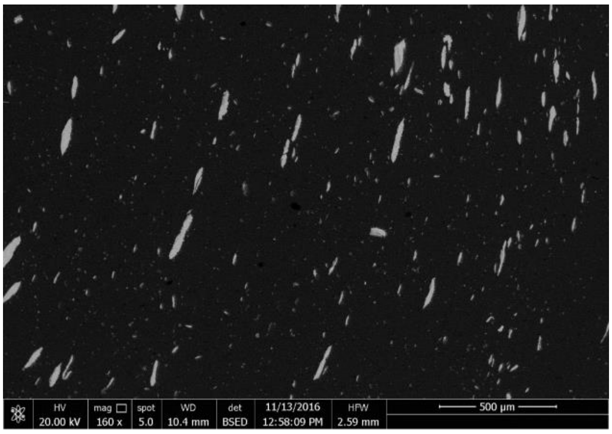

Figure 6: *SEM image of the upper welded area in the aluminum nugget of the best joint*

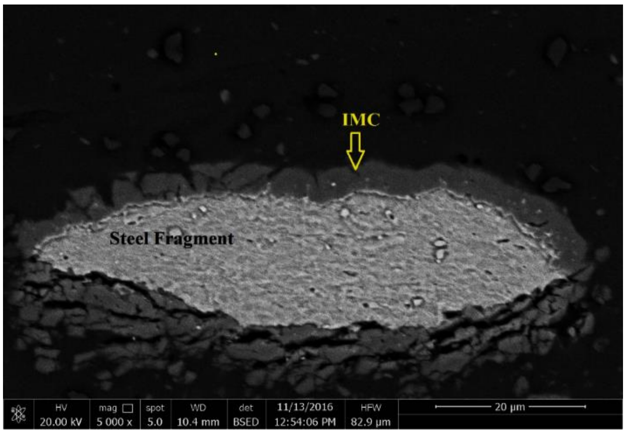

Figure 7: *Enlarged SEM image of a steel fragment in nugget*

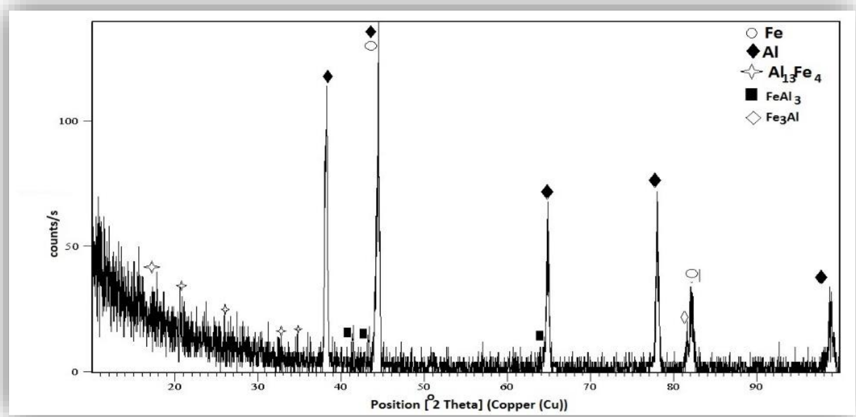

Figure 8: *XRD spectrum of the weld illustrating existence of $FeAl_3$, Fe_3Al and $Al_{13}Fe_4$*

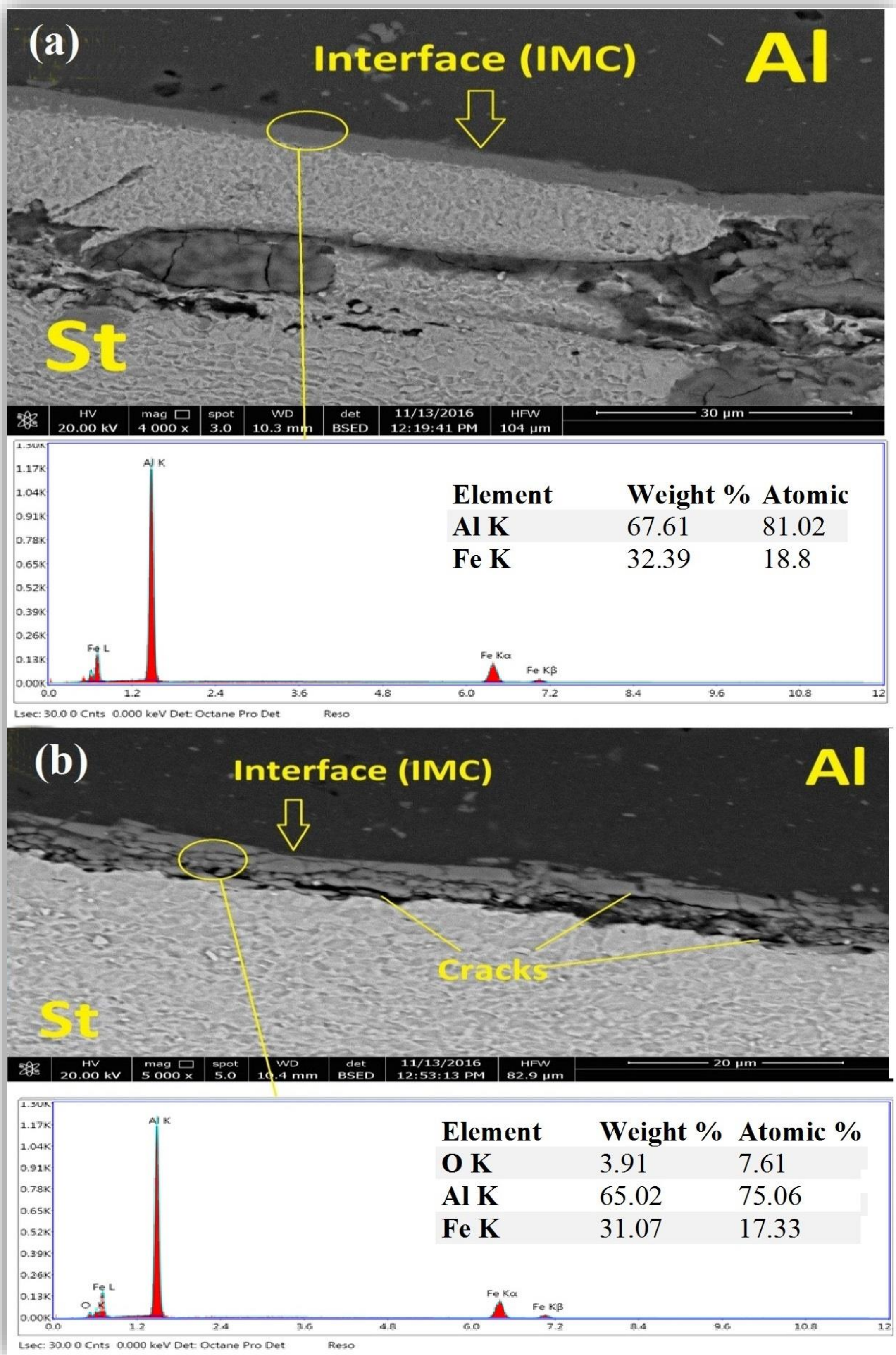

Figure 9: *SEM images and EDS analyses of the interface in the top region (under the shoulder): (a) Zone 1 (b) Zone 2*

4 Conclusion

Dissimilar Friction stir welds between annealed low carbon steel and 1050 pure aluminum were successfully accomplished by using different tool tilt angles, weld location, tool cooling and different tool materials. The maximum UTS achieved in this study is 74.5 MPa under the process variables condition of 1550 rpm rotational speed, 17 mm/min traverse speed, 0.5 mm pin offset to steel side, 2^o tilt angle, 1.6 mm pin length, and K107 tool steel (tool material) with cooling. The maximum joint efficiency, compared to the aluminum tensile strength, is 51.7%. The worst UTS was obtained when the steel was placed on the retreating side. The nuggets were filled with steel pieces sheared off from the steel surface. These particles reacted with the aluminum matrix and produced brittle intermetallic compounds (IMCs). The thicknesses of the IMC at the interface at the upper weld region with tool cooling (with partial cooling of the weld zones) were 3 μm and 7.5 μm. Only the $FeAl_3$ IMC layer was observed at the interface.The tool made of W302 tool steel could not withstand heat and friction under any process variable conditions and the tool wear was observed. The tool made of K107 tool steel could only weld 8 cm without showing any wear with cooling.

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Appendices

Appendix A: Available at URL https://journals.aijr.in/index.php/ajgr/article/view/422/140

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