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Effect of Welding Parameters on Macro and Microstructure of Friction Stir Welded Dissimilar Butt Joints between AA7075-T651 and AA6061-T651 Alloys

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Abstract

Aluminium alloys have gathered wide acceptance in the fabrication of light weight structures requiring a high strength-to weight ratio and good corrosion resistance. Compared to the fusion welding processes that are routinely used for joining structural aluminium alloys, friction stir welding (FSW) process is an emerging solid state joining process was invented in 1991 by TWI, in which the material that is being welded does not melt and recast. The dissimilar friction stir weldability of 7075-T651 and 6061-T651 aluminium alloys was investigated in this study with various process parameters like tool rotational speed, tool welding speed and tool pin profiles. The macro and microstructure, scanning electron microscopy (SEM), energy-dispersive spectroscopy (EDS) were conducted to study the effects of rotational and welding speeds with the pin profiles for dissimilar friction stir welded butt joints keeping AA6061-T651 plate on the advancing side. The good mixing of both the materials joined was obtained at lower welding and higher rotational speed.

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*Keywords:*Dissimilar materials joining,Friction stir welding,Macrostructure,Microstructure,Scanning electron microscopy,Energy dispersive spectroscopy

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1. Introduction

Friction stir welding process is a solid state joining technique considered to be the significant development over the past two decades which was invented and validated at the welding institute (TWI), United Kingdom in the year Thomas et al (1991). The FSW process is explained using Fig.1. In this process no melting occurs and the heat is generated internally by means of friction between the material-tool interface and the plastic deformation takes place without pre or post heating. FSW is immune to the defects and property deteriorations associated with the fusion welding such as melting and coarsening of strengthening phases Mahoney et al (1998). Joints between dissimilar materials of 6061-T6 and 7075-T6 in aerospace structures mostly made by riveting which causes stress concentration and increase the weight of the final joints. Dissimilar welding of aluminium alloys is a core demand of the aircraft industries to substitute the traditional joining technologies with low costs and high efficiency ones such as friction stir welding in the future advanced design. Numerous papers can be found in the literature on various studies related to FSW of dissimilar aluminium alloys.

Nomenclature

FSW	friction stir welding
SEM	scanning electron microscope
EDS	energy dispersive spectroscope
SZ	stirred zone
TMAZ	thermo mechanical affected zone
HAZ	heat affected zone
mm/min	millimetre/minute
rpm	revolution per minute
SS	simple square
TCT	taper cylindrical threaded
TST	taper square threaded

MuhamadTehyo et al (2012) investigated the influence of process parameters on metallurgical and mechanical properties of dissimilar FS welded joint between semi-solid metal 356-T6 and aluminum alloy 6061-T651 and reported that an increase in the welding speed apparently leads to an increase in the tensile strength of the specimen. In fact, the tensile strength reaches a maximum value for a particular welding speed and then decreases as the welding speed is further increased. Sang-Woo Song et al (2010) performed experiment on dissimilar materials namely 5052 and 5J32 and measured the lowest hardness value in the Heat Affected Zone (HAZ)/ Thermo Mechanical Affected Zone (TMAZ) of 5052 while the highest hardness was measured in 5J32. However, these values did not deviate largely from those of base materials. Bahemmat et al (2010) obtained the mechanical, micro and macro structural characteristics of dissimilar friction stir welding of AA6061-T6 and AA7075-T6. Fracture occurs in the TMAZ–HAZ interface of AA6061 due to its lower hardness and strength in the weld. Conversely, due to higher strength, fracture does not arise at the Stirred Zone (SZ). Da Silva et al. (2011) studied the Material flow and mechanical behaviour of dissimilar AA2024-T3 and AA7075-T6 high-strength Al alloys and presented the effect of the threaded profile of the tool pin on material flow and mixing pattern. Moreira et al (2009) studied the mechanical and metallurgical characterization of friction stir welded joints between AA6061-T6 and AA6082-T6 and observed that the lowest hardness value transpired in the AA6082-T6 alloy plate side which leads to rupture during tensile test. Leitao et al (2009) investigated the mechanical behaviour of similar and dissimilar AA5182-H111 and AA6016-T4 and found that both alloys exhibit a hardness variation consistent with the microstructure evolution across the TMAZ. ShanmugaSundaram et al (2010) carried out experiment to obtain tensile behavior of dissimilar friction stir welded joints of aluminium alloys 2024-T6 and 5083-H321 and revealed that the increase in tool rotational speed or welding speed leads to increase in tensile strength, reaches a maximum value and then decreases.

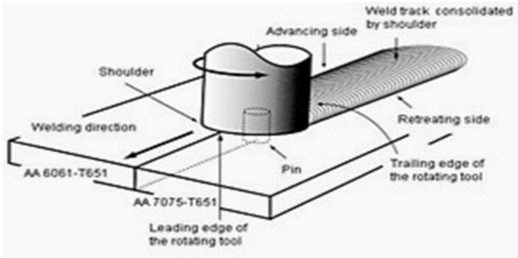

Fig.1 Schematic diagram of friction stir welding process

Tensile elongation decreases with increase in tool rotational speed whereas it increases with increasing the welding speed. Similar studies have been performed by few researchers on dissimilar aluminium alloys and the study on dissimilar aluminium alloys can be further extended particularly on dissimilar FSW between AA6061-T651 and AA7075-T651. Many studies have been conducted to characterize the resulting microstructure in welds especially in dissimilar aluminium alloys. Many researchers studied and reported the base materials microstructure and its properties. However, there are not enough literatures on microstructural characterization of dissimilar materials especially on aluminium alloys between 6000 and 7000 series. The aim of this paper is to present and report the effects welding parameters on macro and macro structural features with SEM and EDAX analysis for dissimilar welds of aluminium alloys between AA7075-T651 and AA6061-T651 produced at different pin profiles.

2. Experimental work

Aluminium alloys of AA6061-T651 and AA7075-T651 are selected to fabricate dissimilar joints using the FSW process. T651, for the above alloys, indicates that both the materials are solution heat treated, stretched and artificially aged. The length, width and thickness of both the aluminium alloy plates are chosen as 100, 50 and 6.35 mm respectively. Chemical compositions and the mechanical properties of AA6061-T651 and AA7075-T651 are given in Tables 1 and 2 respectively. The tools with different pin profiles, weld set up and a typical welded plate are shown in Fig. 2(a), (b) and (c).

Table 1.Chemical composition of base aluminium alloys

Base alloys	Al	Si	Fe	Cu	Mn	Mg	Cr	Ni	Zn	Ti
6061-T651	97.16	0.8	0.4	0.27	0.09	0.96	0.21	0.01	0.06	0.02
7075-T651	89.76	0.05	0.1	1.3	0.03	2.69	0.2	0.01	5.78	0.06

Table 2. Mechanical properties of base aluminium alloys

Aluminium alloys	Yield strength, (MPa)	Ultimate tensile strength, (MPa)	Tensile elongation, (%)	Micro hardness (VHN)
6061-T651	287.0	303.0	17.2	102.0
7075-T651	526.0	583.0	11.3	171.0

Dissimilar friction stir welding process is carried out by placing the high strength aluminium alloy AA7075-T651 at the retreating side (RS), and by placing the aluminium alloy AA6061-T651 at the advancing side (AS); since if the weaker alloy is located at the RS, the fabricated weld will become weaker than when the weaker alloy is at the RS .The process parameters which have the greater influence on the tensile strength of dissimilar FSW joints are identified as rotational speed ,welding speed and tool pin profile.Three different pin profiles (Taper cylindrical threaded (TCT), Taper square threaded (TST) and Simple Square (SS) tools used were machined from H13 tool steel and hardened to 55HRC. Trail experiments are conducted to determine the working and feasible range of process

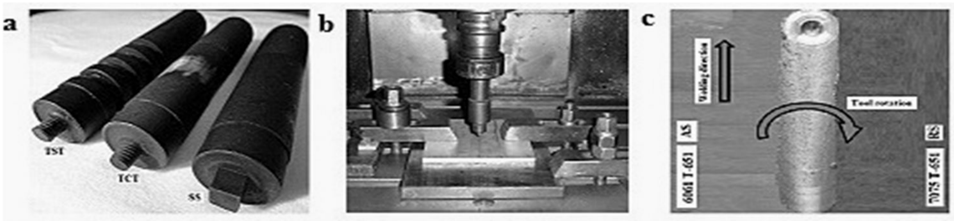

Fig.2 (a) Tool pin profiles, (b) FSW set up, (c) Typical welded plate by FSW process

Table 3.Dissimilar friction stir welding parameters and the selected levels

S. No	Welding parameter	Unit	Levels		
1	Tool rotational speed	rpm	800	900	1000
2	Welding speed	mm/min	90	100	110
3	Tool pin profile	-	SS	TCT	TST

Table 4. Mechanical properties of dissimilar friction stir welded specimens

S.No	Rotational speed (rpm)	Welding speed(mm/min)	Pin profile	UTS (Mpa)	Vicker's Hardness (HV)
1	800	90	TCT	174.08	113.24
2	1000	90	TCT	184.12	110.73
3	800	110	TCT	183.06	112.36
4	1000	110	TCT	178.10	110.35
5	800	100	SS	170.03	110.11
6	1000	100	SS	160.06	106.21
7	800	100	TST	160.10	105.48
8	1000	100	TST	175.10	104.95
9	900	90	SS	170.05	111.78
10	900	110	SS	179.12	109.47
11	900	90	TST	178.01	107.30
12	900	110	TST	175.04	108.33
13	900	100	TCT	205.06	114.12
14	900	100	TCT	205.08	114.21
15	900	100	TCT	205.01	114.22
16	900	100	TCT	205.03	114.21
17	900	100	TCT	204.23	114.13

parameters. The influenced process parameters and their working range for the dissimilar FSW of AA6061-T651 and AA7075-T651 are presented in Table 3. The weld were characterized using DE-WINTOR inverted trinocular metallurgical microscope, Met Mech Engineers, Chennai and Scanning Electron Microscope (SEM) Hitachi S-3400N make from Anna University, Chennai, Tamilnadu, India and Field Emission Electron Microscope (FESEM) SUPRA 5 Carl Zeiss, Germany make from Sathyabama University, Chennai, Tamilnadu, India. Table 4 represents the Mechanical properties of dissimilar friction stir welded specimens.

Results and discussions

2.1. Micro structure for base aluminium alloys

Fig.3 (a) shows the microstructure in which particles of Mg_2Si are evenly precipitated in aluminium solid solution. Some inter metallic's which are undissolved like Al_6 (Fe,Mn) also present in the matrix. The matrix is well solutionized and precipitation hardened. The particles of Mg_2 Al which are present can be resolved at higher magnification whereas Fig.3 (b) shows the matrix typical precipitation hardened matrix with the fine precipitation of Cu-Al_2 along with Mg Zn_2 and complex precipitates of $Cr_2Mg_3Al_{18}$ complete dissolution of Cu-Al_2 and reprecipitation leads to finer particles after solutionising and Age hardening. The high hardness measured shows the precipitation of the strengthening agents are complete.

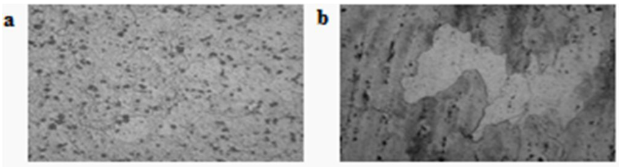

Fig.3 Microstructure of (a) AA 6061-T651 & (b) AA 7075-T651 at 100X

2.2. Macro structure studies for dissimilar welds

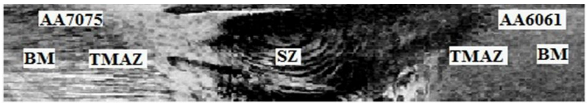

Fig.4 Typical micrograph showing various regions of the FS welded plate at 20X

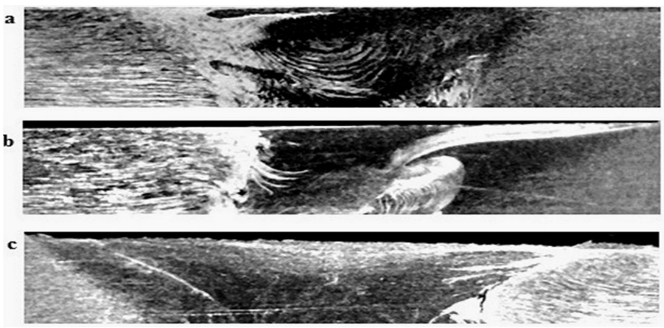

Fig.5 Macro image of transverse cross section at 20X (a) TCT tool with 900 rpm & 100 mm/min (b) TST tool with 900 rpm & 90 mm/min (c) SS tool with 900 rpm & 110 mm/min

Fig.4 shows the micrograph of the produced weld after thoroughly etched with the keller's reagent marked as stirred zone (SZ), thermo mechanical affected zone (TMAZ) and base metal (BM).Fig.5 shows the typical macro images of the transverse cross section for three different process parameters with three different pin profiles Taper cylindrical threaded (TCT), Taper square threaded (TST) and Simple Square (SS).Fig 5(a) indicates the macro image of the cross-section of the butt welded dissimilar plates of heat treatable wrought aluminium alloys namely 7075 on the left and 6061 on the right.The parent metal of 7075 shows the grain flow along the direction of the rolling, and the 6061 shows the fine grain flow. Fig 5(b) indicates the macro image of the cross-section of the butt welded dissimilar plates 7075 on the left and 6061 on the right.The parent metal of 7075 shows the grain flow along the direction of the rolling. And the 6061 shows the fine grain flow. Fig 5(b) indicates the macro image of the cross-section of the butt welded dissimilar plates, 7075 on the right and 6061 on the left.The parent metal of 7075 shows the grain flow along the direction of the rolling while the 6061 shows the fine grain flow.

2.3. Micro structure studies for dissimilar welds

Typical micrographs reveal important features in some of the interfacial regions of the welds produced by this characterization work are hereby presented below.Fig.6 (a)-(f) presents the microstructures in various zones of the joint interfaceof the weld produced at 900 rpm and 100mm/min with TCT tool.Fig.7 (a)-(g) presents the microstructuresin various zones of the joint interface of the weld produced at 900 rpm and 90mm/min with TST tool. Fig.8 (a)-(g) presents the microstructuresin various zones of the joint interface of the weld produced at 900 rpm and 110 mm/min with SS tool.

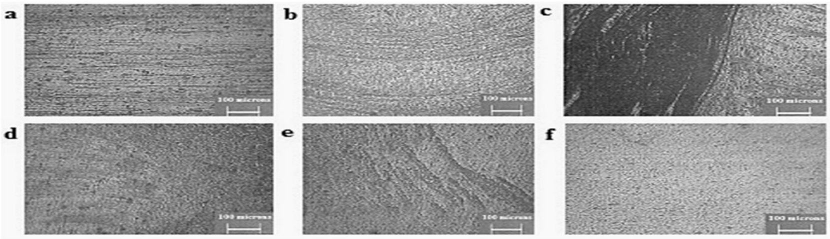

Fig.6 (a)-(f) Micro images of transverse cross section at 100X for TCT tool with 900 rpm & 100 mm/min

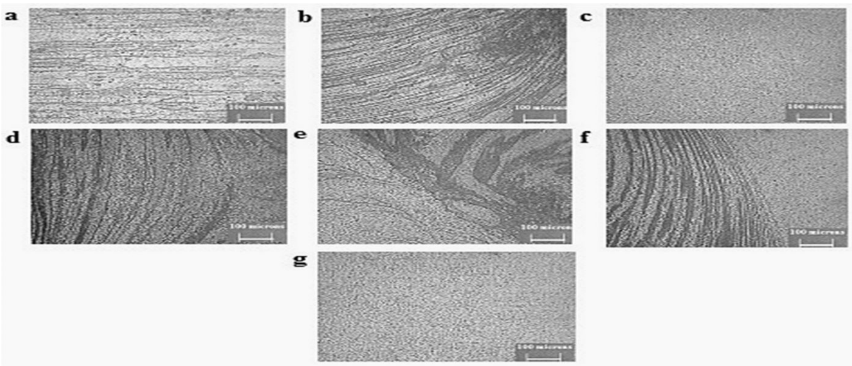

Fig.7 (a)-(g) Micro images of transverse cross section at 100X for TST tool with 900 rpm & 90 mm/min

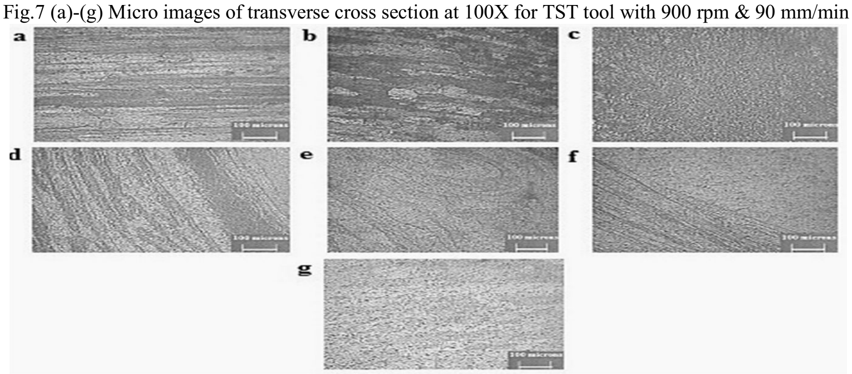

Fig.8 (a)-(g) Micro images of transverse cross section at 100X for SS tool with 900 rpm & 110 mm/min

Fig.6 (a) shows the microstructure of the 7075 in T651 condition solution heated and precipitated treatment. The microstructure shows the grain flow along the direction of rolling. The eutectic particles presents are Cu Al2, Al Mg2 & Zn Al2 as fine precipitates in aluminium solid solution which is the main matrix. Fig.6 (b) represents the FSW zone where alternate layers of 7075 alloy and 6061 alloys are have undergone fusion. The precipitated particles in both have become larger due to heat and stress. Fig.6 (c) shows the interface zone of the parent 7075 with the fusion zone (FSW). Fig.6 (d) shows the FSW zone dominated by 7075 matrix. Fig.6 (e) shows the interface zone of 6061 parent metal with TMAZ zone of alternate layers of 6061 and 7075 alloys. Fig.6 (f) microstructure shows fine particles of Mg_2Si that are precipitated in Aluminium solid solution which the matrix. Fig.7 (b) shows the TMT zone of 7075, where grains are oriented along the stirring direction. Fig.7 (c) represents the FSW zone with completely fragmented particles of eutectic strengthening agents of 7075 and 6061 precipitated. Fig.7 (d) shows the alternate layers of 7075 and 6061 at the FSW zone. Fig.7 (e) shows the FSW zone where alternate layers of 7075 alloy and 6061 alloys are have undergone fusion. The precipitated particles in both have become larger due to heat and stress. Fig.7 (f) shows the FSW zone where alternate layers of 7075 alloy and 6061 alloys are have undergone fusion. The precipitated particles in both have become larger due to heat and stress.

Fig.8 (b) Shows the TMAZ zone of 7075, where grains are oriented along the stirring direction. Fig.8 (c) shows the FSW zone with completely fragmented particles of eutectic strengthening agents of 7075 and 6061 precipitated. Fig.8 (d) represents the FSW zone where alternate layers of 7075 alloy and 6061 alloys are have undergone fusion.The precipitated particles in both have become larger due to heat and stress. Fig.8 (e) shows the FSW zone where alternate layers of 7075 alloy and 6061 alloys are have undergone fusion. The precipitated particles in both have become larger due to heat and stress. Fig.8 (f) shows the TMAZ zone of 6061 forming onion rings and the parent metal 6061 at the right side. Fig.8 (g) microstructure shows fine particles of Mg2Si that are precipitated in Aluminium solid solution which the matrix.

2.4. Scanning electron microscope studies for dissimilar welds

Fig.9 (a, b) shows the SEM images where the regions from the center of the nugget Zones. The zones indicated that a good fusion of the 7075 and 6061 has produced alternate layers with fine grains. The broad band is from 7075 and the light dull areas are from 6061 alloy. The image at Fig.9 (c) shows the dominant 7075 alloy fusion at the nugget zone. Fig.9 (d, e) SEM images, shows the TMT zone of the 7075 with the formation of the onion rings with 6061 alloy. The images indicate the nugget zone with lower percentage of the 6061 alloy forming thin rings. The image at Fig.9 (f) shows the precipitation of the intermetallics at the nugget zone. Fig.9 (g) shows the Image of the parent metal 7075 along the direction of the rolling. The presence of un-dissolved eutectics is at the grain boundaries. The image Fig.9 (h) shows the TMT zone which consists of alternate rings of 7075 and 6061 alloys. The grains are fine and could not be resolved at higher magnifications. From the Fig.10 (a)-(c) it is found that dimple fracture mechanism was occurred with some degree of ductility in mixing these two alloys.

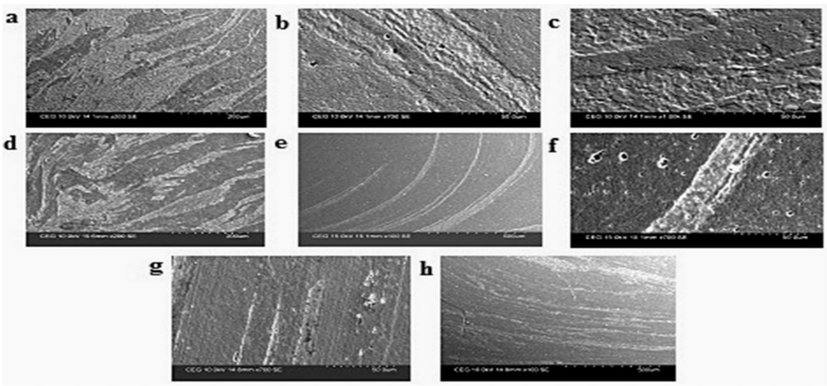

Fig.9 Typical SEM images (a-c) for TCT tool with 900 rpm & 100 mm/min, (d-f) for TST tool with 900 rpm & 90 mm/min, (g-f) for SS tool with 900 rpm & 110 mm/min

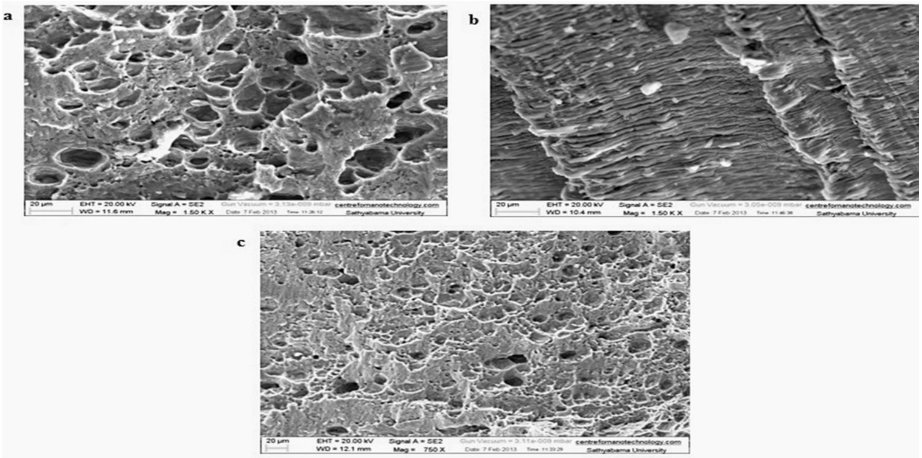

Fig.10 SEM fractographs from the weld cross section at SZ (a) TCT tool with 900 rpm & 100 mm/min (b) TST tool with 900 rpm & 110 mm/min (c) SS tool with 800 rpm & 90 mm/min

2.5. EDAX studies for dissimilar welds

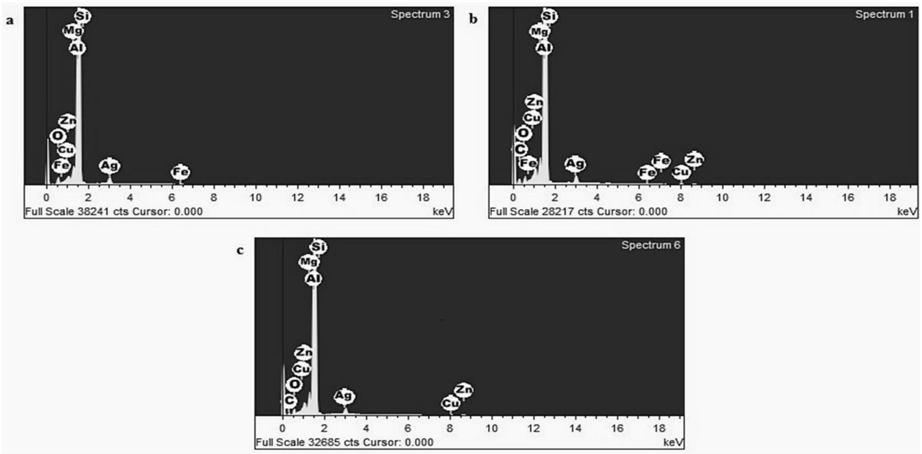

Fig.11 EDAX analysis in nugget area of weld produced at (a) 900 rpm and 100 mm/min for Taper cylindrical threaded profile, (b) 900 rpm and 90 mm/min for Taper Square threaded profile, (c) 900 rpm and 110 mm/min for Simple Square profile

The EDAX analysis in Fig.11 reveals the presence of alloying elements for both aluminium alloys and is well mixed in the nugget area of the weld for all pin profiles used at (a) TCT tool with 900 rpm & 100 mm/min (b) TST tool with 900 rpm & 110 mm/min (c) SS tool with 900 rpm & 90 mm/min.

2.6. Effect of Welding parameters on Micro structure

3.6.1. Rotational Speed

Reference to the optical and SEM images, for any particular welding speed, the tensile strength increases first, reaches a maximum value and then decreases with increasing the rotational speed. Similar trend is observed for the tool pin profiles considered ascending from SS, TCT and TST tools. Generally, the tensile strength is poor at lower rotational speeds due to inadequate tool stirring action. For the rotational speed of 800 rpm, the frictional heat is low causing poor material flow which results in reduction of tensile strength. When the speed of the tool is increased to 900 rpm, the strain hardening effect induced by tool stirring action increases the tensile strength. Conversely, the tensile strength decreases as the rotational speed of the tool is further increased to 1000 rpm. The reason for the same is due to re-precipitation, reduction in dislocation density and coarsening of strengthening precipitates caused by excess frictional heat. Hence the rotational speed of 900 rpm yields higher tensile strength.

3.6.2. Welding Speed

Reference to the optical and SEM images, for a given rotational speed, the increase of welding speed increases the tensile strength to a certain valueand further increase of welding speed results in decrease of tensile strength. Similar behaviour can be observed for welding speed against three different pin profiles of SS, TCT and TST tools. For lowest (90 mm/min) and highest (110 mm/min) welding speeds, lower tensile strengths are observed. The lower welding speed significantly deteriorates the mechanical properties of joints due to larger heat input into the weld samples, however as the welding speed increases, the thermal cycles effect is minimized which leads to an increase in tensile strength. The lower tensile strength at 110 mm/min is due to insufficient frictional heat generated. All the three different tools yield lower tensile strength at the lowest welding speed of 90 mm/min. For all the welding speeds, the TCT tool exhibits higher tensile strength whereas lower tensile strength is observed for TST tool.

3.6.3. Tool Pin Profile

The dissimilar joints fabricated using the TCT tool has maximum tensile strength compared to the joints made using SS and TST tools for any welding and rotational speed.

3. Results and discussions

The following conclusions are drawn from the present study:

- The maximum tensile strength of 205.23 MPa occurs for Taper cylindrical threaded profile with the rotational speed of 900 rpm and welding speed of 100 mm/min whereas, for the parameters 900 rpm and 90 mm/ min, Taper Square threaded profile yields lower tensile strength of 178.01 MPa. The reason for the lower value can be attributed to the poor fusion of the two plates and this is evident from the macro images which show larger discontinuity at the butt area.
- The EDAX analysis reveals that the constituents of 7075 and 6061 are present at the nugget zone for the three combinations that yield higher tensile strength.
- It is observed from the Optical and SEM graphs that there is uneven distribution of two materials (7075 and 6061) in the nugget zone for the combinations 900 rpm and 100 mm/min (Taper square threaded profile) and 900 rpm and 110 mm/min (Simple Square profile) which yields tensile strength of 178.01 MPa and 179.12 MPa respectively.
- The taper cylindrical threaded tool exhibits good tensile strength of 205.23 MPa compared to other tools.

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