Metallurgical Characterization and Hardness Evaluation of Dissimilar Friction Stir Welded Al Alloy Flat Plates

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Abstract. Friction Stir Welding (FSW) is commonly developed for welding of metals of the same kind like aluminium copper, steel and titanium. However, FSW also has the potential to produce high-quality joints between dissimilar metals which are differ in physical and mechanical properties. In this work dissimilar aluminium alloys plates of AA 6101-T6 and AA 6351-T6 with 6 mm thick were friction stir butt welded under the influence of different process parameters. The influence of various parameters, particularly the rotational speed on microstructures and hardness properties of the joints has been addressed. The microstructure of weld joints has been studied using an optical microscope and distinct zones are also identified. Fine-equiaxed and refined grains are observed at nugget zone of dissimilar joints due to effective stirring action of cylindrical profile tool pin at higher tool rotational speeds. The intermetallic compounds that form in the joints has been examined by the X-ray diffraction (XRD) and the presence of intermetallic compound Mg_2Si in base metals and FSW joints was detected. Therefore, it can be understood that the intermetallic compound affects the hardness of butt joints. The highest and lowest SZ hardness are obtained with the welds fabricated with 1300rpm, 60 m/min, 4kN and with 900 rpm, 60 mm/min and 8kN respectively.

1. Introduction

Friction Stir Welding (FSW) is a new welding technique invented at The Welding Institute (TWI) in 1991[1]. High quality welds can be produced in metals mostly aluminum, nickel, magnesium, titanium and steel which have large application in automobiles, aerospace and shipbuilding industries [2]. It has been proved that FSW widely used for joining the un-weld able metals [3]. In FSW, a non-consumable rotating tool has been plunged between the interface of two plates to be joined and traversed along the joint line at selected speed and welding speed [4,5] . In FSW, the work pieces do not melt and needs a proper thermal metal flow dynamics [6]. Recently the FSW technique has been used for joining aluminum, magnesium alloys, copper, steel, composites and dissimilar metals [7-8]. By FSW, a better quality of joint can be fabricated using aluminum alloy mostly AA6XXX series which are heat treatable comparing to fusion welding process and similar to gas metal arc welding process [9, 10]. In this experimental study, AA6351aluminum alloy has been selected and this alloy has very useful applications in shipbuilding because of its high strength capacity, corrosion resistance, better processibility and weldability [11]. AA6101-T6 aluminum alloys are mostly applicable in electrical industries for its high electrical conductivity and good mechanical properties. Therefore joining of these two dissimilar alloys has great importance in electrical industries. T6 is the temper designation for two dissimilar aluminum alloys to get maximum mechanical property i.e. solution heat treated and artificially aged. N. T. Kumbhar et al. [12] worked on FSW of two aluminum alloys AA6061 and AA5052 at different level of tool rotation speeds and tool welding speeds. From the microstructure studies, they observed that in the nugget zone there was no severe inter mixing of both materials. They observed that tensile strength of the dissimilar FSW joints (AA5052&AA6061) is better than the tensile strength of FSW joints between AA6061&AA6061.Ranjith R. et al. [13] worked on FSW of dissimilar aluminum alloys AA2014 T651 and AA6063 T651. They observed satisfactory intermixing and bonding of metals formed by tool tilt angle 40° .They found better tensile property keeping the tool offset towards AA2014 side by complete fusion of harder metal. S. Ravikumar et al. [14] studied the influence of rotational and welding speeds with the pin profiles on micro hardness and tensile strength of the dissimilar Aluminum AA6061-T651 and AA7075- T651 joints. They found that at lower welding and higher rotational speed, good intermixing of both the metals occurs at weld joint interface. Aging heat-treated aluminum alloys (A2xxx, A6xxx, A7xxx) and solid solution-hardened (A5xxx) alloy have vital industrial uses which are discussed in [15, 16]. These material microstructure and mechanical characterization changed severely during FSW. The age heat-treated alloys hardness depends on the density distribution of strengthening precipitates.

Figure 1. Friction Stir Welding Experimental Setup
(With permission from NIT, Trichy)

To the best of our knowledge, There is limited work reported on dissimilar FSW of AA6101 Aluminum alloy and AA6351 Aluminum alloy is done at varying rotational speed .The objective of this work is to study the metallurgical characterization and hardness evaluation on dissimilar aluminum alloys joints fabricated via FSW .

2. **Experimental procedure**:

AA6101-T6 and AA6351-T6 aluminum alloys in plate form of 6 mm thick are used as base metals in this study. Two plates are kept in the butt joint manner and the weld direction is perpendicular to the rolling direction of both plates.AA6101-T6 and AA6351-T6 alloys chemical compositions are shown in Tables 1. AA6101-T6 and AA6351-T6 alloys mechanical properties are shown in Table 2. In this study, four different joints are made by computerized FSW machine shown in Figure 1. At the advancing side AA 6101-T6 was placed and in the retreating side AA6351-T6. The plates were rigidly clamped with zero root gaps to prevent separation during welding from the joint line. The FSW tool was fabricated with EN32 tool steel having a surface hardness of 65 HRC and then oil hardened. The cylindrical threaded pin profile having tool tilt angle 2º has been use for this study. The flat faced shoulder diameter and pin diameter were fixed at 18 mm and 6 mm respectively. The tool geometry, welding speed and rotational speed are selected based on combinations as per literature and the capability of the FSW machine used for this study. Four welded samples are prepared with different rotational speeds keeping welding speed constant. The welding process parameters used for study are presented in Table 3.

Table 1. Base metals chemical compositions used in this study.

Aluminum Alloys	Cu	Mg	Si	Fe	Mn	Al
6101 T6	0.05	0.65	0.5	0.5	0.03	rest
6351 T6	0.10	0.80	0.95	0.60	0.70	rest

Table 2. Base metals mechanical properties used in this study.

Al Alloy	UTS (MPa)	Y.S. (MPa)	Elongation (%)	Hardness (VHN)
6101T6	220	195	15	71
6351T6	310	285	14	95

Table 3.Process parameters used in this study.

Process and tool parameters	Values
Tool rotational speed (rpm)	900, 1100, 1300 and 1500
Welding speed (mm/min)	60
Axial force (kN)	8, 5, 4 and 6
Tool shoulder diameter, D (mm)	18
Tool pin diameter, d (mm)	6
Tool pin length (mm)	5.85
D/d ratio of tool	3

For the study the microstructure and hardness properties, the FSW joints were sliced using a power hacksaw and then machined to as per dimensions. The test specimens having 30mm length,10mm width and 6mm thick are taken from the cross-section, ground, polished and then etched with Keller’s reagent. The microstructures study was carried out by optical microscope. Hardness across the weld joint was taken on a cross-section perpendicular to the weld direction using micro-Vickers hardness tester at 10 gram force and 15 seconds dwell time. The intermetallic compounds present in weld zone of dissimilar joints were characterized by X-ray diffraction (XRD) analysis.

3. Results and Discussion:

3.1 Macrostructure study

Friction Stir Welding of dissimilar aluminum alloys of AA6101- T6 and AA6351-T6 were carried out by varying rotational speeds. Dissimilar joint of Aluminum AA6101- T6 to AA6351-T6 found satisfactory in visual inspection and surface morphology. The crown and macrostructures of the FSW joints are shown in Figure. 2. The crown shows the smooth appearance with absence of voids, cracks, depressions and excessive flashes. The macrostructure of the dissimilar joints reveals evident that the joint has no defects such as tunnels, piping or worm hole. The various well-defined zones have been observed in all welds joints made by FSW. The macrostructure consists of base metal zone (BMZ), heat affected zone (HAZ), thermo mechanically affected zone (TMAZ) and nugget zone (NZ) or stirred zone (SZ). A distinct boundary exists between the TMAZ& HAZ.

FSW designation	Rotational speed (rpm)	Completed dissimilar weld joint crown appearance	Macrograph of dissimilar joints
DS1	900		
DS2	1100		
DS3	1300		
DS4	1500		

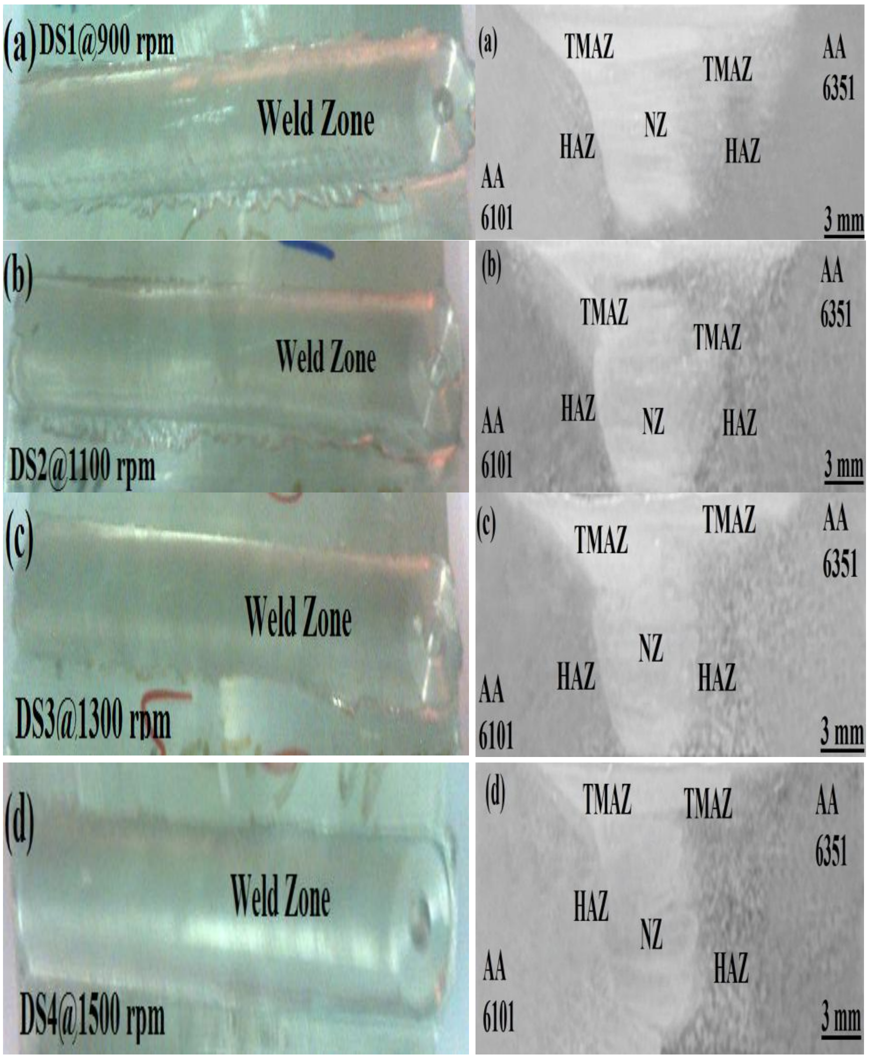

Figure 2. Crown appearance and Macrostructure of dissimilar joints at different rotational speeds

3.2. Microstructures examination

The base metal (AA6101) consists of coarser and elongated grains microstructure in rolling direction shown in (Figure. 3(a)) and also comprises of coarse grains of aluminum with the hardening precipitates of Mg_2Si. Figure 3(b) shows the base metal microstructure of AA6351 aluminum alloy. The grains are relatively smaller and finer than AA6101 aluminum alloy. The quality of dissimilar joints is observed not only from the macrostructure but also the interior region of the weld.

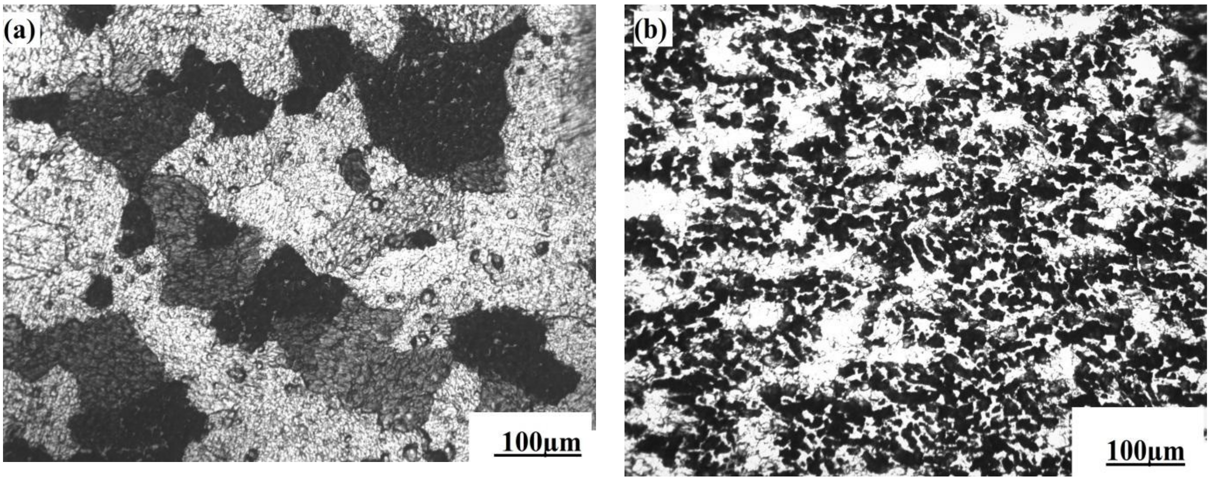

Figure3. Optical microstructure of base metals: (a) AA6101 Al alloy; (b) AA6351Al alloy

The stir zones microstructures of all dissimilar joints are shown in Figure. 4(a-d). It is evident from the figures that at 900 rpm and 1100rpm microstructure of SZ shows mixed flow of two metals. It is due to the friction generated between the shoulder and the pin with the base metal surfaces being welded by effective stirring action of toolat definite rotational speed.

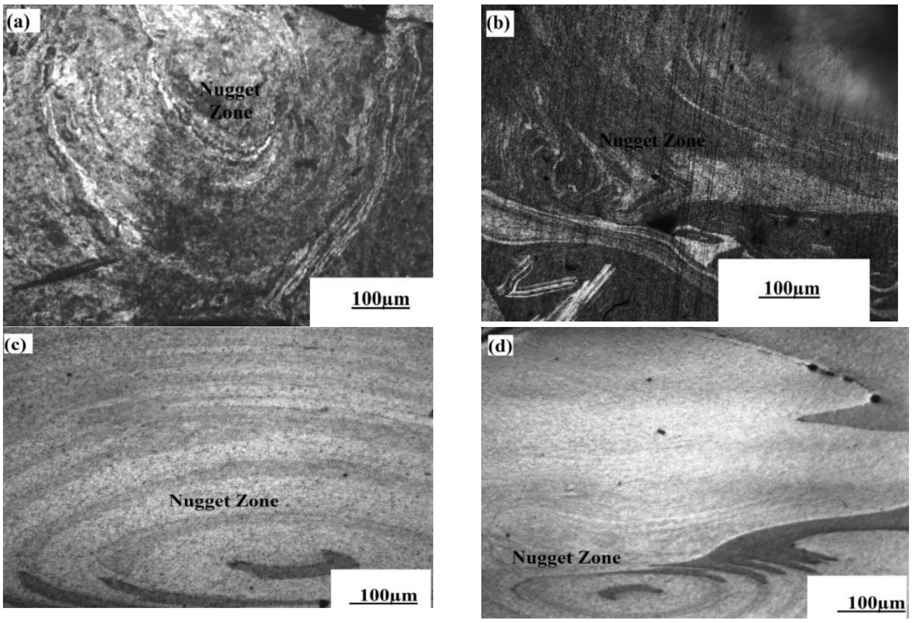

Figure4. Microstructures of stir zones shows banded structure using different rotational speeds of (a) 900rpm (b) 1100rpm (c) 1300rpm (d) 1500rpm.

Microstructure of alternating band structure in the form of "onion rings" was observed in SZ at rotational speed 1300rpm because of high heat generation and uniform distribution of intermetallic compound Mg_2Si with fine refined grain structures. The temperature in the SZ sufficiently high at 1500rpm which lead to the dissolution or growth of some precipitates which affect the hardness of the weld joint. The grains are elongated in TMAZ and shows considerable distortions because of the mechanical action generated by welding tool. The grain structure in HAZ resembles with base metal and this zone is mechanically not affected by the FSW tool. Figure 5(a-h) shows the interfacial boundary between the TMAZ and HAZ revealing the difference in the grain size clearly from respective side.

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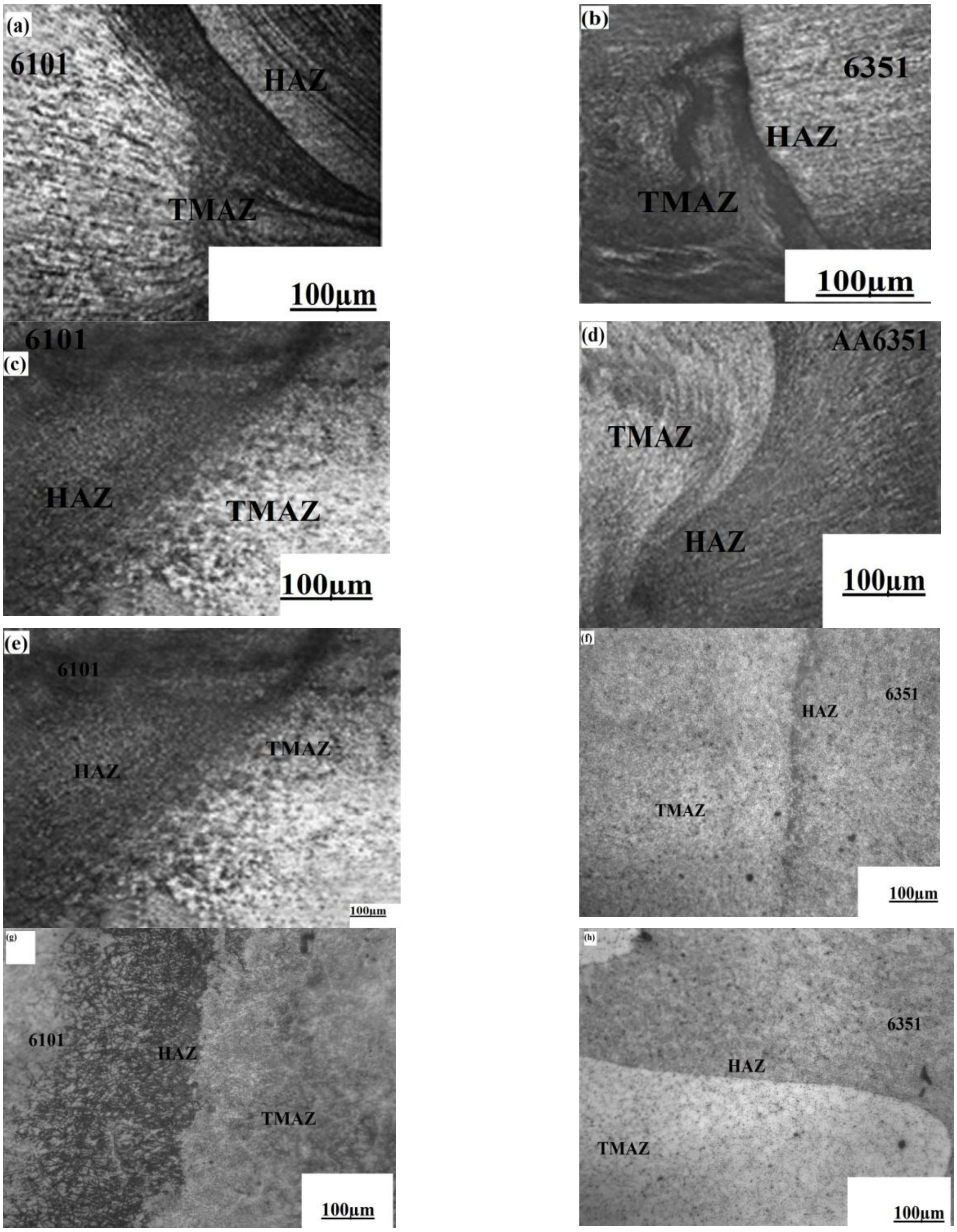

Figure 5. Weld interface microstructure at different rotational speeds of (a-b) 900rpm (c-d) 1100rpm (e-f) 1300rpm (g-h) 1500rpm

3.3XRD study

X-ray diffraction (XRD) analysis has been taken on transverse cross-sections of the FSW welds and the corresponding patterns for the base metals and FSW joints are shown in Fig. 6. Based on XRD peaks the presence of Al phase and Mg_2Si was confirmed in parent metals and FSW joints. All FSW joints (disimillar) were shows comparable strength than base metals due to the presence of intermetallic compound Mg_2Si.

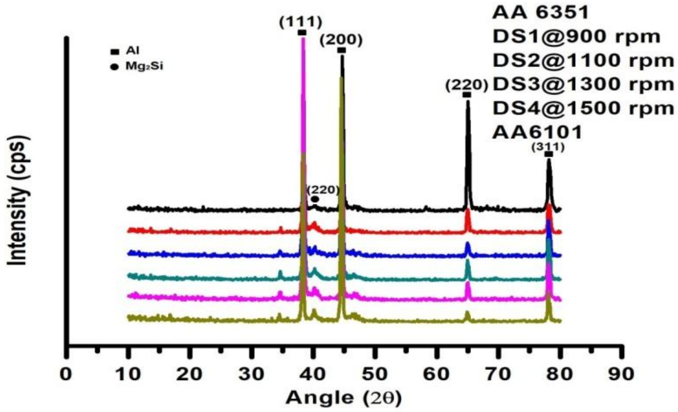

Figure6. XRD patterns obtained from base metals and dissimilar weldsat variable tool rotational speed.

3.4. Hardness Measurements

The distribution of hardness across the weld obtained for the samples are shown in the Fig.7. From the graph it observed that the rotational speed affect the hardness of the weld joints. The hardness variation occurs because of difference in heat generation during FSW which also affect the base metal microstructures .The hardness depends on the precipitate distribution such as Mg_2Si.The joint made by the rotating speed of 1300 rpm, welding speed of 60 mm/min exhibits optimum hardness value at weld nugget zone. This is because of uniformly distribution of fine equiaxed grains and strengthening precipitates (Mg_2Si) [17] when rotational speed increases to 1500rpm there is drop in the hardness due to high heat softening occurs at SZ which leads to breaking of strengthening precipitates (Mg_2Si).

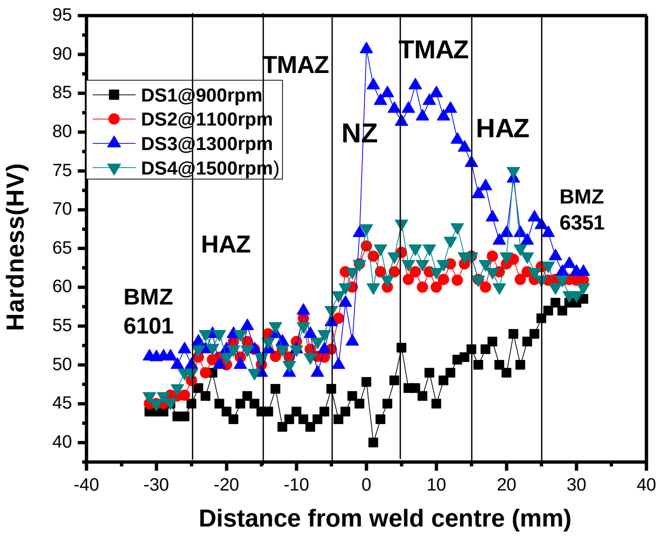

Figure7. Hardness test graph of dissimilar FSW joints

4. Conclusions

FSW of dissimilar aluminum alloys carried out at successfully with selected welding process parameters which produces sound welds without any welding discontinuities. In the optical microstructure, the SZ, HAZ and TMAZ were clearly observed for all the FSW joints. X-ray diffraction (XRD) analysis confirmed the presence of intermetallic compound Mg_2Si in base metals and FSW joints. Fine-equiaxed and refined grains are observed at nugget zone of dissimilar joints due to effective stirring action of cylindrical profile tool pin at higher tool rotational speeds. The grain structure in heat affected zone (HAZ) resembles with the base metal and this zone is not mechanically affected by the FSW tool. The peaks presence of Al phase and Mg_2Si was confirmed in parent metals and FSW joints with XRD study. The joint made by the rotating speed of 1300 rpm & welding speed of 60 mm/min exhibits optimum hardness value at weld nugget zone. This is because of uniform distribution of fine equiaxed grains of strengthening precipitates (Mg_2Si) and when rotational speed increases to 1500rpm there is drop in the hardness due to high heat softening occur sat SZ which leads to breaking of strengthening precipitates (Mg_2Si).

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