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Key words: FSW, aluminium alloys AA6082, tool pin geometry, weld speed, mechanical and metallurgical characterization

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EFFECT OF TOOL GEOMETRY AND WELDING SPEED ON MECHANICAL PROPERTIES AND MICROSTRUCTURE OF FRICTION STIR WELDED JOINTS OF ALUMINIUM ALLOYS AA6082-T_6

Friction stir welding is a solid state innovative joining technique, widely being used for joining aluminium alloys in aerospace, marine automotive and many other applications of commercial importance. The welding parameters and tool pin profile play a major role in deciding the weld quality. In this paper, an attempt has been made to understand the influences of welding speed and pin profile of the tool on friction stir welded joints of AA6082-T_6 alloy. Three different tool pin profiles (tapered cylindrical four flutes, triangular and hexagonal) have been used to fabricate the joints at different welding speeds in the range of 30 to 74 mm/min. Microhardness (HV) and tensile tests performed at room temperature were used to evaluate the mechanical properties of the joints. In order to analyse the microstructural evolution of the material, the weld's cross-sections were observed optically and SEM observations were made of the fracture surfaces. From this investigation it is found that the hexagonal tool pin profile produces mechanically sound and metallurgically defect free welds compared to other tool pin profiles.

1. Introduction

Friction stir welding (FSW) is a solid-state joining process developed and patented by The Welding Institute (TWI) [1-2], and has emerged as a welding technique used in high strength alloys (2xxx, 6xxx, 7xxx and 8xxx series) for aerospace, automotive and marine applications [3] that were difficult to join with conventional techniques. This technique is attractive for joining high strength aluminium alloys since there is far lower heat input during

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the process compared with conventional welding methods such as TIG or MIG. This solid state process leads to minimal micro-structural changes and better mechanical properties than conventional welding [3-5]. The process was developed initially for aluminium alloys, but since then, FSW was found suitable for joining a large number of materials. Conventional fusion welding of aluminium alloys often produces a weld which suffers from defects, such as porosity developed as a consequence of entrapped gas not being able to escape from the weld pool during solidification. In contrast with FSW, the interaction of a non-consumable tool rotating and traversing along the joint line creates a welded joint through viscoplastic deformation and consequent heat dissipation resulting in temperatures below the melting temperature of the materials being joined. Other interesting benefits of FSW compared to fusion processes are low distortion, excellent mechanical properties in the weld zone, execution without a shielding gas, and suitability to weld all aluminium alloys [6]. The working principle of FSW process is represented in Fig. 1. Comparative microstructural and mechanical properties studies of base material and friction stir welded joints have been performed by several authors. Some authors analysed the influence of the tool rotation speed [7-8], welding speed [9-13] and both parameters simultaneously on the microstructure and mechanical properties of 6XXX welds [14-17]. The weld joints produced by FSW have been reported to have joint tensile properties of 80-100% of the base material [13-14]. These works enhance the difficulty in evaluating the dependence of the thermal and mechanical properties on weld parameters. The mechanical and metallurgical behaviour of dissimilar welds as a function of processing parameters has been widely studied, showing the behaviour of AA6082-AA6061 materials [18]. In present investigation an

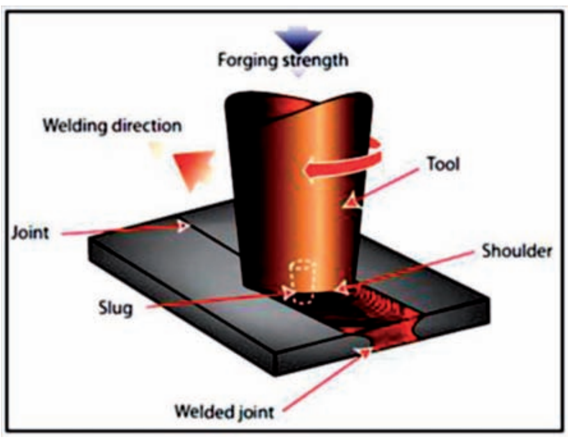

Fig. 1. Principle of FSW process

attempt has been made to understand the effect of various tool pin profiles and different welding speed on the weld of aluminium alloy 6082 in annealed and solutionized and aged conditions.

FSW joints usually consist of four different regions as shown in Fig. 2. They are: A-Weld nugget (WN), B-Thermo-mechanically affected zone (TMAZ), C-Heat affected zone (HAZ), and (D) Parent material (PM). The formation of above regions is affected by the material flow behaviour under the action of rotating non-consumable tool. However, the material flow behaviour is predominantly influenced by the FSW tool profiles, FSW tool dimensions and FSW process parameters [13-14].

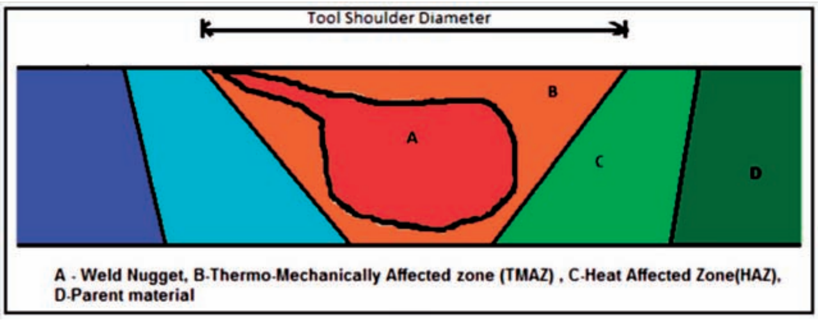

Fig. 2. Different regions of FSW joint

This paper presents the results of an experimental setup in which the aluminium alloy AA6082-T_6 was friction stir welded using various combinations of process parameters (rotational and welding speed). Mechanical properties of the test welds were assessed by means of static tensile test. Macro and microstructure of the welds were examined by means of optical observations and Vickers hardness measurement.

2. Experimental Procedure

The experiments were conducted on the aluminium alloy AA6082-T_6, its chemical composition and mechanical properties are respectively presented in Table 1. The rolled plates of 5 mm thickness were cut into the required size (300 mm×150 mm) by power hacksaw cutting and grinding. Square butt joint configuration was prepared to fabricate FSW joints. The initial joint configuration was obtained by securing the plates in position using mechanical clamps. The direction of welding was normal to the rolling direction. Single pass welding procedure was used to fabricate the joints. In present work, three tool pin profile were used for the welds, made of cold work die steel. The tool pin geometry used is shown in Fig. 2. The machine used for the production of the joints was vertical machining centre.

Table 1.
Chemical composition and mechanical properties of aluminium AA6082

Chemical Composion								
Element	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti
Required	0.7-1.3	0.5	0.1	0.4-1.0	0.6-1.2	0.25	0.2	0.1
Contents	0.9	0.24	0.9	0.7	0.7	0.06	0.04	0.05
Mechanical Properties (Temper-T6)								
Tensile Strength (MPa)		Yield Strength (MPa)		Elongation (%)		Hardness (HV)		
Min	Max	Min	Max	Min	Max			
295	–	240	–	8	–	89		
324	332	308	319	9	12	90		

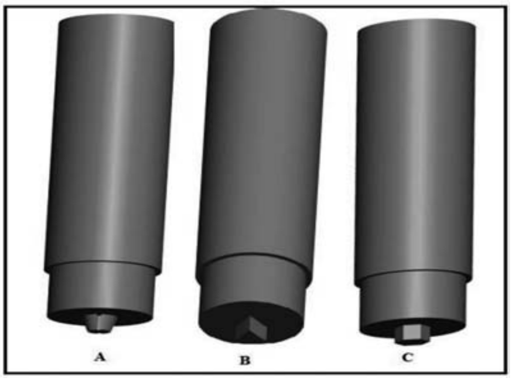

Fig. 3. Tool pin geometry used (A) Four flute pin (B) Triangular pin (C) Hexagonal pin

Table 2.
Welding conditions employed to join aluminium AA6082 plates

Weld Process Parameter	**Values**
Rotational Speed (rpm)	1600-1650
Welding Speed (mm/min)	30-74
Tool Depth (mm)	4.6
Tool shoulder Diameter (mm)	18
Tilt Angle (degree)	0

The welding parameters and tool dimensions are presented in Table 2. The welded joints were sliced using pantograph machine to the required dimensions to prepare tensile specimens. American Society for Testing of Materials (ASTM E8-04) guidelines was followed for preparing the test specimens. Tensile test was carried out in 400 KN capacity mechanical controlled universal testing machine and mechanical properties -ultimate tensile stress (UTS) yield strength (YS) and % elongation were measured.

Friction stir welded samples were visually inspected in order to verify the presence of possible macroscopic external defects. X-Ray radiographic inspection was carried out on FSW samples. In radiographic test, 6Ci & Ir192 was used as radioactive source. The film used was Agfa D-4 and the radiographs indicated defect-free weld as well as weld with defects like insufficient fusion and cavity.

Micro indentation hardness test as per ASTM E-384:2006 has been used to measure the Vickers hardness of FSW joints. The Vickers microhardness indenter is made of diamond in the form of a square-base pyramid. The test load applied was 100 gram and the dwell time was 15 seconds. The indentations were made at midsection of the thickness of the plates across the joint.

Scanning electron microscopy (SEM) has been used for tensile fractured surfaces analysis.

Metallographic specimens were cut mechanically from the welds, embedded in resin and mechanically ground and polished using abrasive disks and cloths with water suspension of diamond particles. The chemical etchant was the Keller's reagent. The microstructures were observed on optical microscope.

3. Result and Discussion

3.1. Mechanical properties

Transverse tensile properties of FSW joints such as yield strength, tensile strength, percentage of elongation and joint efficiency have been evaluated. It can be inferred that the tool pin profile and welding speed are having influence on mechanical properties of the FSW joints. Engineering stress strain curves and effect of welding speed on mechanical properties for three pin profiles are shown in Figs. 4 to 6.

Of the three joints, the joints fabricated by hexagonal tool profile exhibited superior tensile properties of 198 MPa with joint efficiency of 54.24% (Fig. 6) compared to other joints, irrespective of welding speed. Though the tensile strength and hardness values are lower than the base metal, the joint efficiency is acceptable one when compared to conventional fusion welding process with low joint efficiency not exceeding 50%. Considering pin profiles, the joints fabricated by triangular pin profiled tool are also showing similar results of tensile properties (Fig. 5) to that of the joints fabricated by hexagonal pin profiled tool. However, the joints fabricated by tapered four flutes pin profiled tool exhibited inferior tensile properties compared to their counterparts, irrespective of welding speed used as shown in Fig. 4.

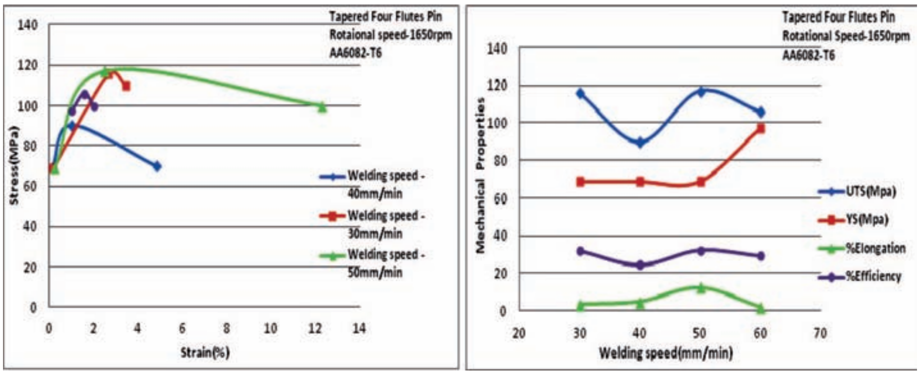

Fig. 4. Engineering stress strain curves and effect of welding speed for four flute pin

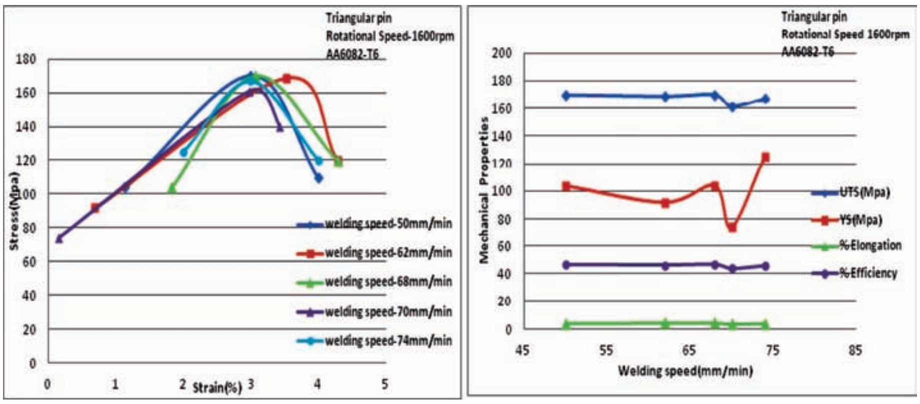

Fig. 5. Engineering stress strain curves and effect of welding speed for triangular pin

The joints fabricated at a welding speed of 40 mm/min by tapered four flutes (Fig. 4) have shown lower tensile strength, elongation and weld joint efficiency compared to the joints fabricated at a welding speed of 68 mm/min and this trend is common for all the tool profiles. Similarly, the joints fabricated at a welding speed of 50 mm/min have also shown lower tensile strength and elongation compared to the joints fabricated at a welding speed of 68 mm/min. The effect of welding speed is concerned, the joint fabricated at a welding speed of 68 mm/min by hexagonal pin is showing superior tensile properties compared to other joints, irrespective of tool profiles (Fig. 6).

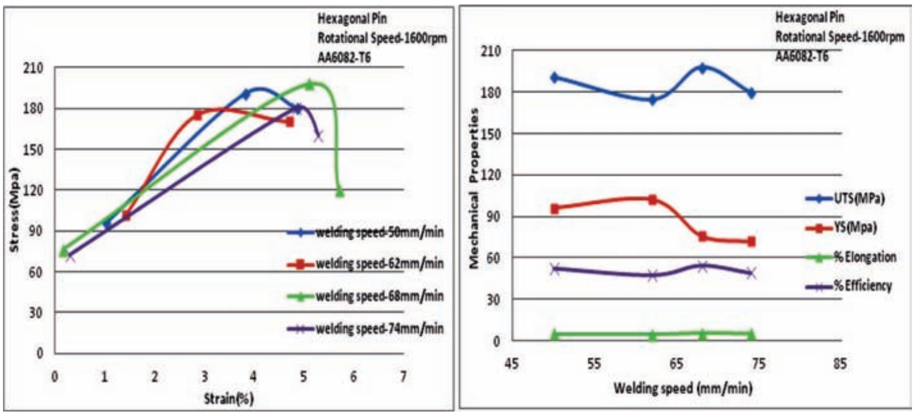

Fig. 6. Engineering stress strain curves and effect of welding speed for hexagonal pin

3.2. Effect of tool pin profile

The principal function of the non-consumable rotating tool pin is to stir the plasticized metal and move the same behind it to have good FSW joint. Tool pin profile plays a vital role in flow of material and in turn regulates the weld speed of the FSW process. The pin generally has cylindrical plain, frustum tapered, threaded and flat surfaces. Pin profiles with flat faces like hexagonal and triangular are associated with eccentricity. This eccentricity allows incompressible material to pass around the pin profile. Eccentricity of the rotating object is related to dynamic path due to eccentricity and is the part of the FSW process. The relationship between the static and dynamic volume decides the path for the flow of plasticized material from the leading edge to the trailing edge of the rotating tool. The triangular and hexagonal pin profiles produce an energetic stirring action in the flowing material due to flat faces. Of the three joints, the highest hardness value of 86.65 HV (Fig. 7) has been recorded in the joint fabricated using hexagonal pin profiled tool and the lower hardness value has been recorded in the joint fabricated by four flutes pin profiled tool. Similarly, the friction stir region of the joint fabricated using hexagonal pin profile tool contains finer grains (Fig. 9) compared to other joints. The higher number of pulsating action experienced in the stir zone of hexagonal pin profiled tool produces finer grained microstructure with uniformly distributed precipitates and in turn yields higher strength and hardness. In case of four flutes pin profiles without flat faces, there is no such pulsating action and the plasticized material is simply allowed to extrude on the sides of the pin resulted in poor tensile strength and joint efficiency.

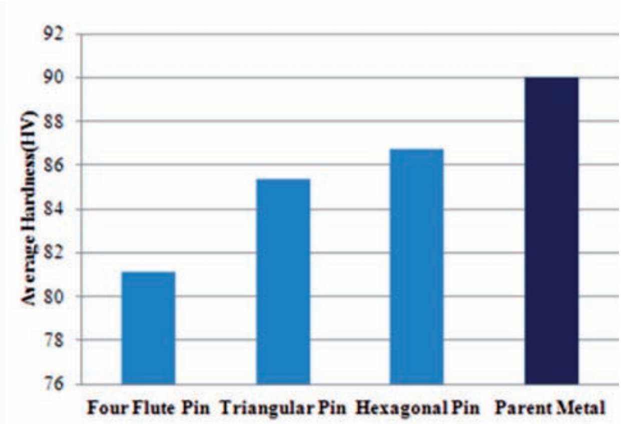

Fig. 7. Average Hardness of AA6082-FSW joint for tool pin profiles

3.3. Effect of welding speed

The heat input in the weld area is affected by welding conditions like welding speed and rotational speed. With constant rotational speed (1600-1650 rpm), higher welding speed resulted in lower heat input per unit length of the weld, causes lack of stirring in the friction stir processing zone yielded poor tensile properties. Lower welding speed resulted in higher temperature and slower cooling rate in the weld zone causes grain growth and precipitates. Most of the joints fractured at the retreating side are due to variation in temperature distribution and flow of the material in the weld zone with corresponding hardness distribution and strained region. It can be observed that the flow of the base material on the advancing side and the retreating side are different. The material on the retreating side never enters into the rotational zone, but the material on the advancing side form the fluidized bed near the pin and rotates around it (Fig. 8). Hence the weld zone is heterogeneous and there is variation in flow of material on retreating and advancing sides. Moreover, due to various zones deform differently, the strain becomes localized, which induces constraint and fracture occurs, where the strain localization is maximum.

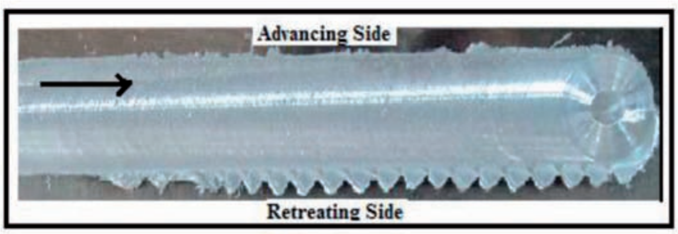

Fig. 8. Advancing and Retreating side of FSW joint of AA6082-T_6

Of the different welding speeds in the range of 30-74 mm/min, the joints fabricated at a welding speed of 68 mm/min exhibited superior tensile properties (Fig. 6), irrespective of tool pin profiles. The combined effect of higher number of pulsating stirring action during metal flow and an optimum welding speed may be the reason for superior tensile properties of the joint fabricated at a welding speed of 68 mm/min using hexagonal pin profiled tool.

3.4. Micro-structural evolution

Based on optical micro structural characterization of grains and precipitates, three distinct zones have been identified such as weld nugget zone, thermo-mechanically affected zone (TMAZ) and heat affected zone (HAZ). The effects of differences in tool geometry and weld process parameters were also investigated by means of a micrographic analysis. Figures 9 to 11 show the optical micrographs of the cross-sections perpendicular to the tool traverse direction of the FSW plates.

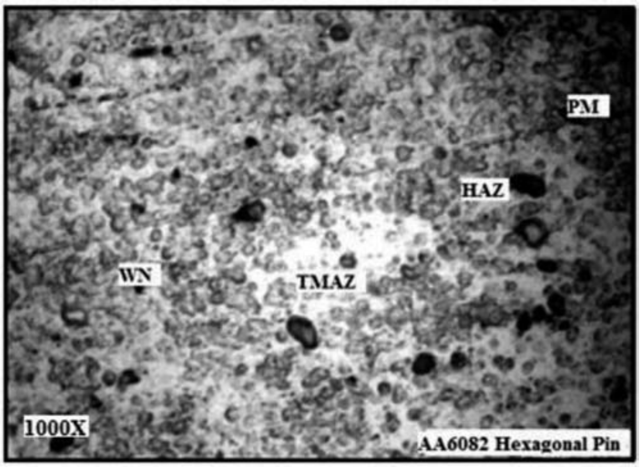

Fig. 9. Microstructure at different zones of AA6082 observed hexagonal pin

The weld nugget zone (WNZ) has experienced high-temperature and extensive plastic deformation, and is characterized by a dynamically recrystallized, fine equiaxed grain structure.

3.5. Fractography analysis

Inspection of the tensile fracture surfaces of AA6082 was prepared at low as well as at high magnification in order to identify the fracture mechanisms. The SEM observations of the fracture surfaces of the tensile tested specimens

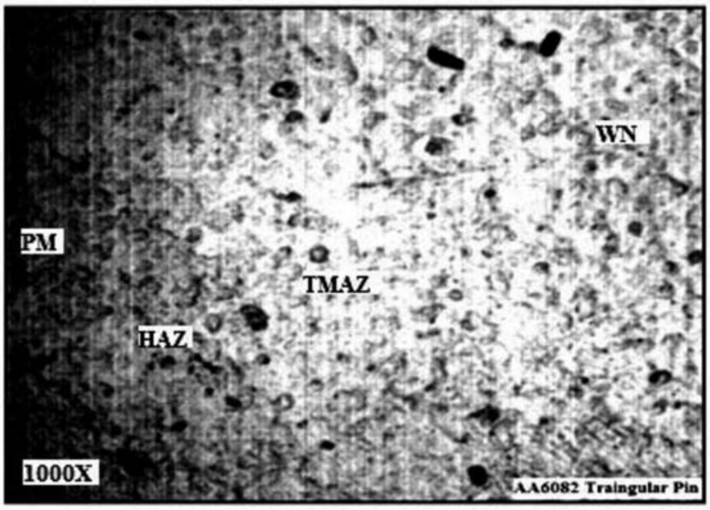

Fig. 10. Microstructure at different zones of AA6082 observed triangular pin

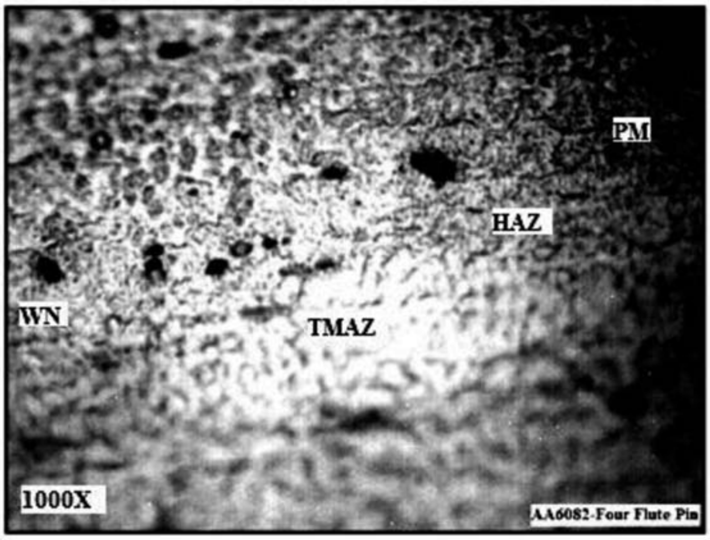

Fig. 11. Microstructure at different zones of AA6082 observed four flutes pin

revealed the best bonding characteristics of the FSW joints. In FSW joints of triangular and hexagonal pin, the fracture surface appears populated of very fine dimples revealing a very ductile behaviour of the material before failure (Figs. 12-13).

Cleavage cracking is the most easily recognizable transgranular brittle fracture observed in FSW joint fabricated by four flute pin (Fig. 14). In

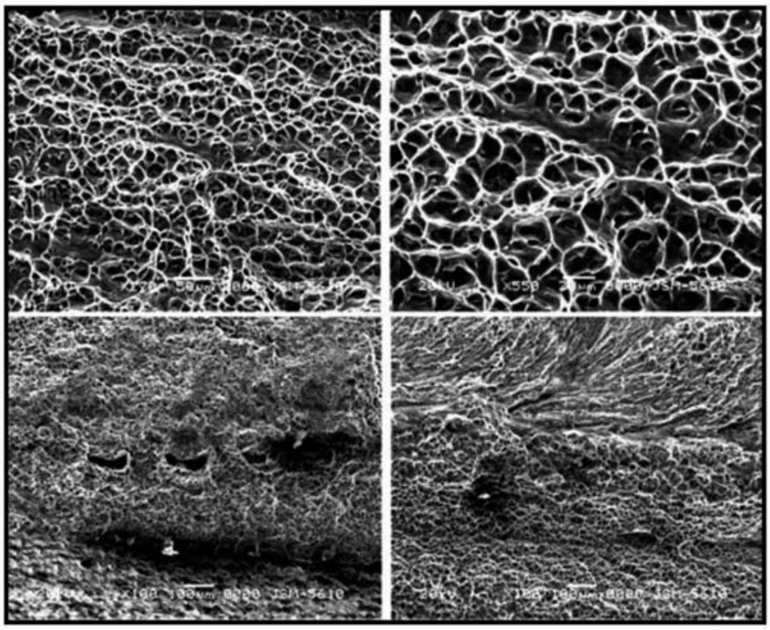

Fig. 12. Tensile fractured surface of AA6082, hexagonal pin at 62 mm/min

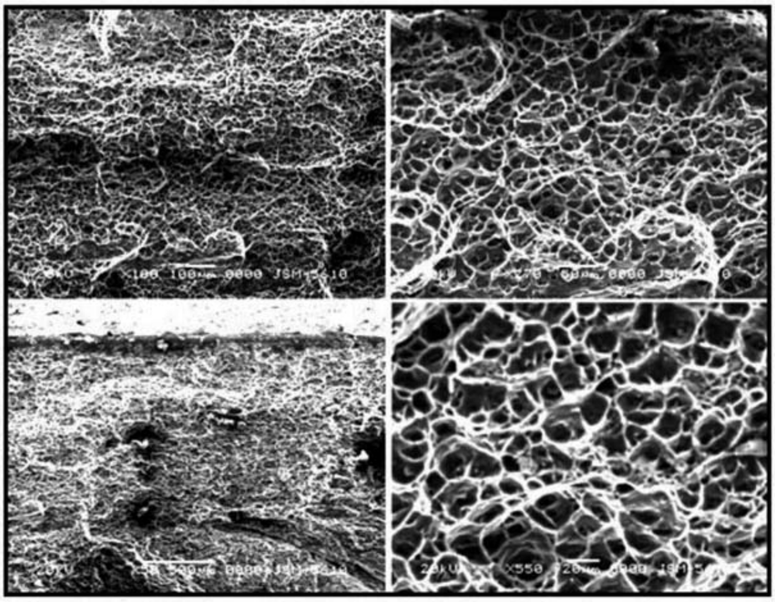

Fig. 13. Tensile fractured surface of AA6082, triangular pin at 50 mm/min

cleavage fractures, the crack separates the metal grains along a well defined crystal plane, initiates at the grain edge, and requires little energy for propagation other than that necessary for crack surface generation.

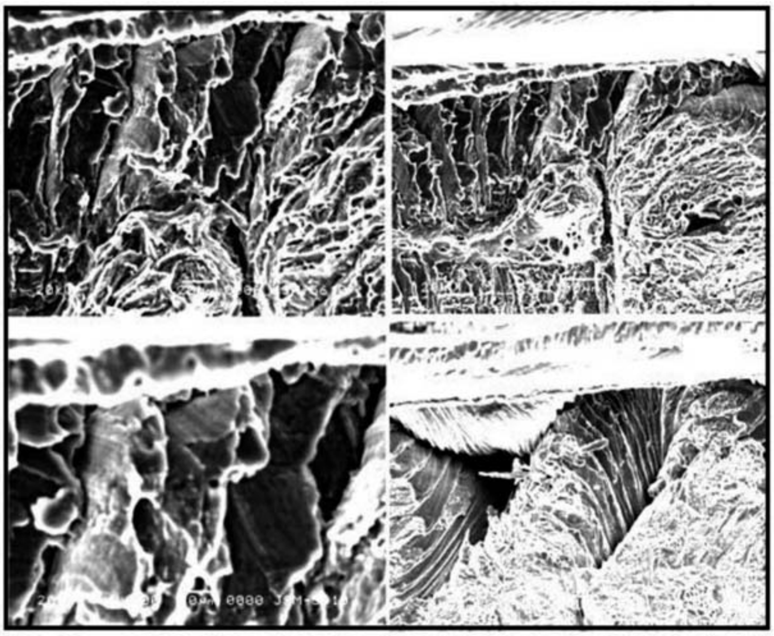

Fig. 14. Tensile fractured surface of AA6082, four flute pin at 60 mm/min

4. Conclusions

The mechanical and microstructural behaviour of AA6082-T_6 was studied in this research paper. The joints were produced with different welding speed from 30 to 74 mm/min and rotational speed of 1600-1650 rpm. Downward force was observed to be the same and it was found to be independent of the weld process parameter for all the produced joints. The mechanical properties of the FSW joint are lower than that of the parent metal. With the increase in welding speed above critical value, tensile strength and % elongation decreases due to low heat input at constant downward pressure and tool rotational speed. Of the three different pin profiles geometry, the joints fabricated by hexagonal pin profile at a welding speed of 68 mm/min exhibited superior tensile properties of 198 N/mm^2 UTS and joint efficiency of 54.24%. Microstructural changes induced by the friction stir welding process were clearly identified in this study. Friction stir welding of AA6082-T_6 resulted in a dynamically recrystalized zone, TMAZ and HAZ. The fracture surface appears populated of very fine dimples revealing a very ductile behaviour of the material before failure in joint fabricated by hexagonal and triangular pin while transgranular brittle fracture observed in FSW joint fabricated by four flute pin.

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Wpływ geometrii narzędzia i szybkości spawania na właściwości mechaniczne i mikrostrukturę spawów wykonanych techniką spawania tarciowego z przemieszaniem w stopach aluminium AA6082-T6

Streszczenie

Spawanie tarciowe z przemieszaniem (FSW) jest innowacyjną techniką spawalniczą stosowaną szeroko przy łączeniu stopów aluminiowych w lotnictwie, przemyśle okrętowym, motoryzacyjnym i w wielu innych istotnych komercyjnie zastosowaniach. Parametry spawania i profil trzpienia narzędzia grają główną rolę gdy chodzi o jakość spawu. W pracy podjęto próbę zbadania wpływów szybkości spawania i profilu trzpienia na spawanie tarciowe z przemieszaniem stopu AA6082-T_6. Trzy różne profile trzpienia (zwężający się cylindryczny z czterema żłobkami, trójkątny i sześciokątny) były używane do wykonania spawów przy różnych szybkościach spawania w zakresie od 30 do 74 mm/min. W celu oceny właściwości mechanicznych spawów wykonano badanie mikrotwardości (HV) oraz testy na rozciąganie w temperaturze pokojowej. Dla oceny mikrostrukturalnej ewolucji materiału przeprowadzono obserwacje przekrojów spawu metodą optyczną, a obserwacje powierzchni pęknięć przy pomocy elektronowego mikroskopu skaningowego (SEM). Na podstawie badań stwierdzono, że zastosowanie sześciokątnego profilu trzpienia narzędzia daje spawy solidne mechanicznie i wolne od defektów, lepsze niż dla pozostałych profili trzpienia.