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Mechanical properties and microstructure studies in Friction Stir Welding (FSW) joints of dissimilar alloy – a review

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ABSTRACT

Purpose: Friction stir welding (FSW) is a relatively new solid state joining process that uses a non-consumable tool to join two different material without melting the workpiece material. Friction stir welding (FSW) was developed for microstructural modification of metallic material. This review article provides an overview of effect of FSW/FSP mechanism responsible for the formation of weld, microstructure refinement, wear of FSW tool and mechanical properties. This review conclude with recommendations for future research direction.

Design/methodology/approach: Heat is generated by friction between the rotating tool and the workpiece material. This joining process is energy efficient, environment friendly and versatile.

Keywords: Friction Stir Welding; Microstructure; Hardness; Tensile strength; Tool wear

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PROPERTIES

1. Introduction

Friction Stir Processing (FSP)/FSW is a method of changing the properties of a metal through intense localized plastic deformation. This deformation is produced by forcibly inserting a non-consumable tool into the workpiece and revolving the tool in a stirring motion as it is pushed laterally through the workpiece. The antecedent of this technique, friction stir welding is used to join multiple piece of metal without creating the heat affected zone typical of fusion welding (Fig. 1). Efficient joints in terms of strength of aluminium matrix composite materials cannot be achieved by fusion based welding method due to the reaction between reinforcements and matrices leading to the formation of brittle secondary phase in the weld pool or decomposition of reinforcements on molten metal [1,2].

As a versatile material, aluminium matrix composites may be selected as an alternative to high strength aluminium alloys in aero engines and aerospace structures like fins, wing and fuselage. In 2001 NASA used composite aluminium AL-Li 2195 rather than aluminium alloy Al2219 for the external fuel tank of space shuttles leading to a reduction of weight by 3400 kg. The saving in weight increases the cargo capacity of space shuttles and enables it to transport more than one components in a single flight to the international space station [3]. Titanium alloy are used extensively in the aerospace industry due to their excellent structure efficiency and good high temperature strength. Welding is an effective way to produce a structure with complex geometry and multiple components. Titanium alloys are readily fusion weld able. However, some problems associates with fusion welding of titanium alloys include porosity, distortion and formation of coarse cast grain structure [4,5].

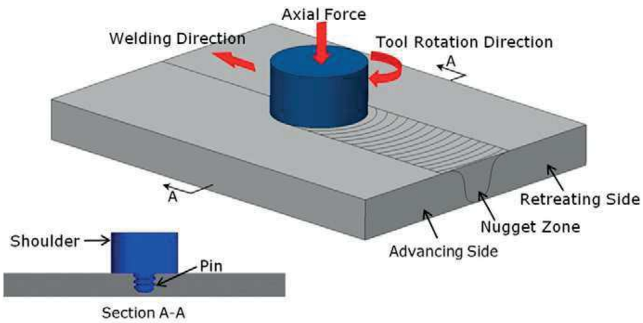

Fig. 1. Friction Stir Welding

2. Literature review

A large number of tool deformations occurred during the first 3 inch length welding trial, the tool configuration changed slightly due to reduced stress on the deformed pin part and tool size and weight decreased continuously. The stress induced cracks were responsible for the majority of tool weight loss.

The defect were found in a region with bimodal microstructure of α+ transformed β phase, which indicate local processing temperature below β- transus due to low heat input [6]. The heat affected zones of a friction stir weld of aluminum alloy 7050-T651 were investigated and compare with the unaffected base metal. Composition of 7050-T651 are 5.7-6.7 Zn, 1.9-2.6 Mg, 2.0-2.6 Cu, 0.08-0.115 Zr. The rotation speed of pin was 350 rpm and travel speed was 15mm/min. Compared to parent material microstructure, the strengthening precipitates have coarsened severely and the precipitate free zone along the grain boundaries has increased by factor of five during friction stir welding, The original base metal grains structure is completely eliminated and replaced by a very fine equiaxed grain structure in the dynamic re-crystallized zone (DXZ). The DXZ consisted of re-crystallized, fine equiaxed grains on the order of 1-4 μm in diameter. Most of the DXZ grains contained a high dislocation density with various degree of recovery from grain to grain [7]. Friction stir processing has been successfully used formation of nano grains and increase the mechanical properties i.e. surface hardness, wear resistance, tensile and fatigue strength.

It was observed that when there is increment on travelling speed, hardness value will also be increased. However increased rotation speeds resulted in lower hardness value at the same travelling speed. Processing parameter including tilt angle and target depth are crucial produce sound and depth free processed region. Friction stir processing result insignificant temperature rise with in and around the weld. A temperature rise of 400-500°C has been recorded within the stir zone for aluminium alloy. The temperature rise result in significant micro structural evaluation i.e. fine re-crystallized grains of 0.1-18 mm, texture, precipitate dissolution and coarsened and residual stress with a much lower magnitude [8].

2.1. Mechanical properties of FSW joints

The investigation of mechanical properties including tensile strength, hardness, and fatigue strength is important particularly for critical component. It is also possible to optimize the welding parameter based on the evaluation of these properties which reflect the joint efficiency.

Tensile strength

Friction stir welding technology requires a thorough understanding of the process and consequent mechanical properties of the weld in order to be used in the production of component for aerospace application. For this reason, detailed research of friction stir welding is required. Friction stir welding can be used to join a different member of material, the primary research and industrial interest has been join aluminium alloy. Defect free welds with good mechanical properties have been made in a wide variety of aluminium alloys, thickness from 1 mm to more than 35 mm will not be welded by friction stir welding. In addition, friction stir weld can be accomplished in any position. [9-15]. The ultimate tensile strength and hardness of bimetallic weld joint increases by increasing the pre-stress, and ductility was decreases when thermal loading increases. For preventing brittle failure behaviour of carbon steel the value of pre-stress and thermal stress should be low as possible [16,17]. The stress strain behaviour of friction stir processing Al-4Mg-1Zr as shown in Figure 2. The optimum strain rate for maximum elongation at 525°C was $1x10^{-1}$ s^{-1}. This show that high strain super plasticity can be achieved in the Al-4Mg-1Zr alloy by FSP.

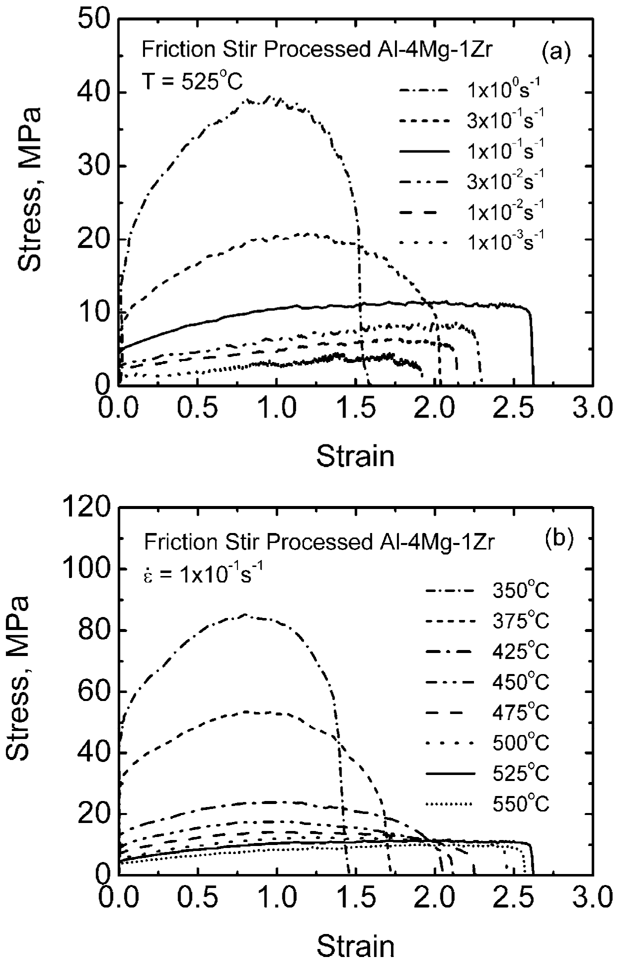

Fig. 2. Stress strain behaviour of friction stir processing Al-4Mg-1Zr, (a) initial strain rate at 525°C, (b) temperature at an initial strain rate $1x10^{-1}$ s^{-1} [18]

Superplastic deformation behaviour of friction stir processing Al-4Mg-1Zr alloy was investigated in strain rate range of $1x10^{-3}$ to 1 s^{-1} and temperature range of 350°-550° and compared with that of as-rolled one. The maximum elongation of 1280% was obtained at 525°C. FSP resulted in significant decrease in the flow stress in Al-4Mg-1Zr alloy. The tested specimen of friction stir processing Al-4Mg-1Zr alloy deformed to failure at 525°C for different strain rates and at $1x10^{-1}$ s^{-1} for different temperature. The specimen show neck free elongation that is characteristic of superplastic flow. The strain rate sensitivity of FSP Al-4Mg-1Zr increases with increasing initial strain rate at investigated strain rates > $1x10^{-3}$, whereas the as-rolled alloy exhibited a nearly constant strain rate sensitivity throughout the investigated strain rate range at 450° C FSP Al-4Mg-1Zr exhibited an increasing m value of 0.12-0.55 in the initial strain rate ranges of 10^{-3} to 10^{-1} s^{-1}. Similarly, the strain rate range sensitivity of FSP Al-4Mg-1Zr at 525°C increases from 0.15 at low strain rates to 0.53 at high strain rates as shown in Figure 2 (a) [18].

The tensile properties of the as-extruded material and the weld with different FSW processing parameters are shown in Figure. 3. The ductility of weld 1 was improved to 11.6% with a slight decrease in strength compared the as-extruded material. A further enhancement in ductility to 14.7% was observed in weld 2, with an accompanying loss of yield strength from 633 MPa to 568 MPa. This decrease in strength is likely to be a result of microstructure coarsening.

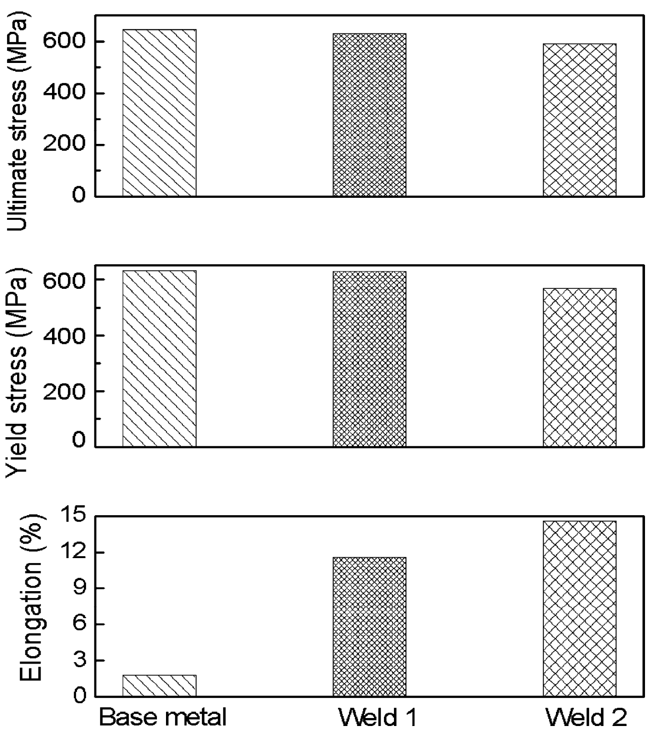

Fig. 3. Tensile properties of as-extruded material weld 1 and weld 2 at room temperature [18]

2.2. Microstructure of friction stir welding joint

The basic concept of friction stir welding is remarkably simple. A rotating tool with pin and shoulder is inserted in a single piece of material for microstructure modification and transversed along the desired line to cover the region of interest. Friction between the tool and workpieces resulted in localized heating that softens and plasticizes the workpiece. A volume of processed material is produced by movement of material from the front of the pin to the back of the pin. During this process, this results in significant grain refinement [19,20].

The presence of a fine grained microstructure is a critical criterion for super plasticity friction stir processing has been shown to have potential as a technique for the production of superplastic aluminium alloy. However, the extent of super plasticity in friction stir processing parts is limited at elevated temperatures due to the evolution of a very coarse-grained microstructure [21-24].

The FSP is very effective technique to fabricate surface metal matrix composite with well distributed particles and very good bonding with metal substrate. The advantages of the FSP are evident compared with laser processing, high energy electron beam irradiation and casting sinter [25].

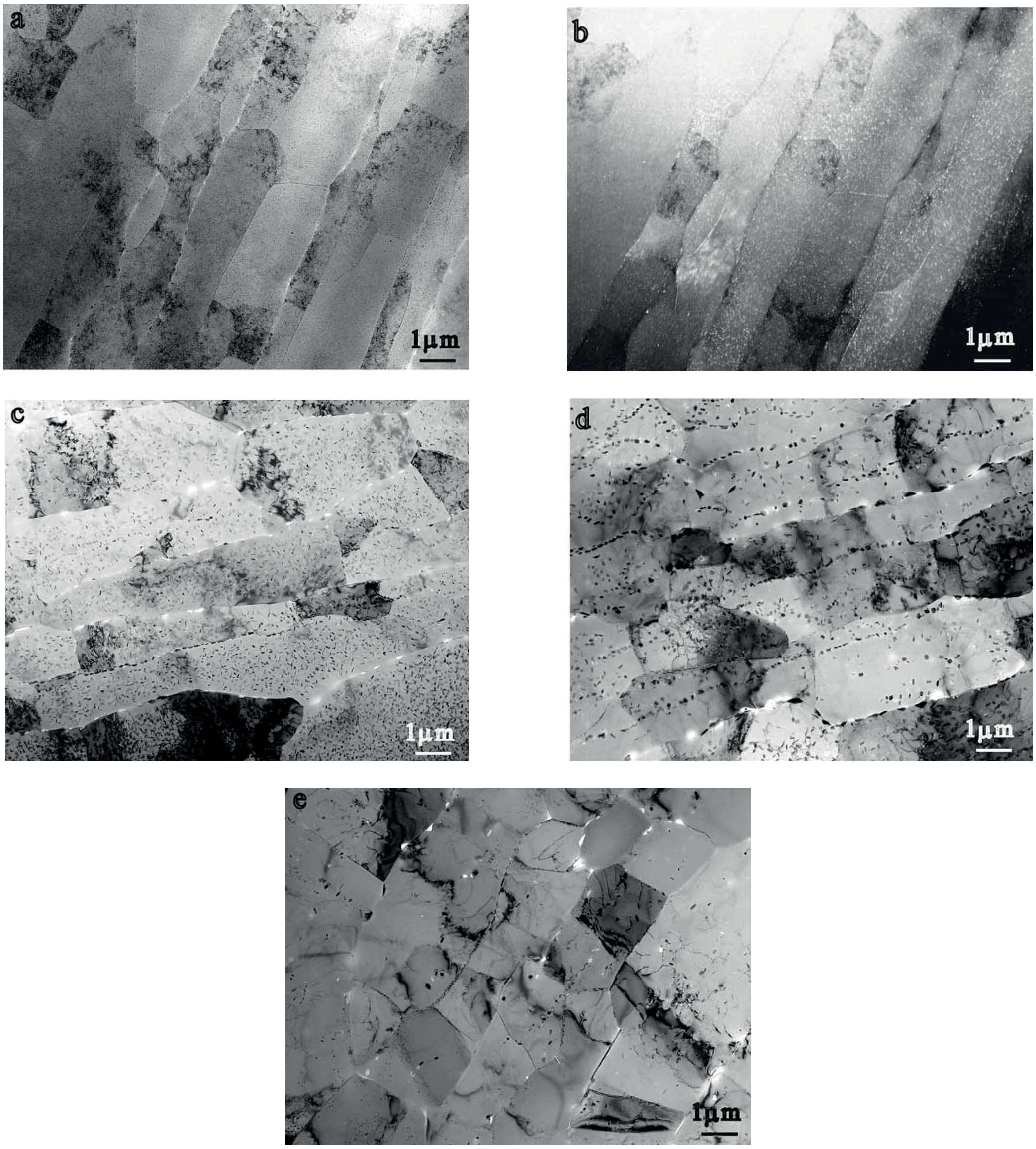

Fig. 4. Grain structure in different weld regions: (a) base metal, (b) dark field image of region (a), (c) HAZ, (d) TMAZ I, (e) TMAZ [26]

The grain structure in the base metal and weldment are shown in low magnification transmission electron microscopy (TEM) photo graph as shown in Figure 4. The microstructure in the parent alloy shows partially recrystallized pancake shaped grains with un-recrystallized region containing sub grains of about 1-5 μm (Fig. 4a). The small difference in diffraction contrast between neighbouring grains in the dark field image shows the dominance of low angle boundaries (Fig. 4b). The grains structure in the HAZ region, which has not been disturbed mechanically by Friction stir welding (FSW), is similar to that of the base metal, (Fig.4c). Grains in base metal and HAZ contain a relatively low dislocation density. The thermos-mechanically affected zone (TMAZ), located between the parent metal and the dynamically recrystallized zone (DXZ), is characterized by a highly deformed structure. With coursing of sub grains, the elongated base metal grains have been pre-served in the TMAZ (Fig. 4d) [26].

The influence of process parameter and FSP run configuration on the stability of nugget microstructure at elevated temperature has been evaluated. All single pass runs showed some extent of abnormal gain growth (AGG), whereas multi pass runs were more resistance to AGG. Cast Al-Alloy of F357 we used for this study. This alloy belongs to the hypoeutectic family of Al-Si system. The occurrence of abnormal grain growth increase when the tool rotation rate is reduced from 2236 rpm to 1500 rpm. The most notable feature of this investigation is the observation of change in the microstructural response of the nugget towards AGG as a function of number of passes inside the nugget. The multiple pass does not resulted in Si particles refined beyond a certain limit. The multi pass run of second configuration indicate that the extent of AGG can be reduced if the material is FSPed multiple times.

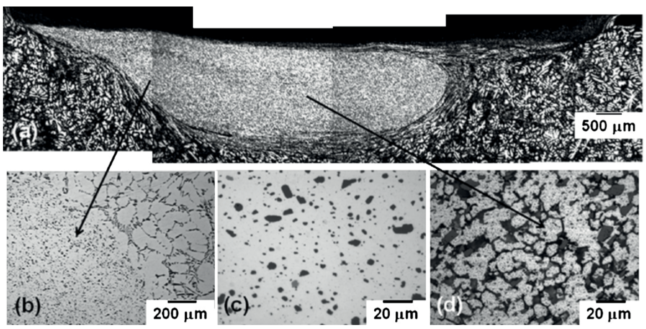

Fig. 5. (a) Cross-section optical macrograph of a single pass run, (b) interface between cast and FSPed region showing extent of particle refinement, (c) higher magnification image shows size and shape of Si particles inside the FSPed nugget and (d) grain structure inside the nugget [27]

Fig. 5a shows an optical macrograph of a single pass run cross-section in which a typical basin shaped nugget can be clearly identified. Eutectic Si particles inside the nugget went through a complex material flow and as a result were highly refined. The extent of refinement is apparent in Fig. 5b, which shows the interface of the cast and FSPed region. The size and shape of refines Si particles get clearer in the higher magnification image Fig. 5c. The typical grain structure of the FSPed nugget is shown in Fig. 5d. The grains were mostly equiaxed, although in a few instance some grains aligned parallel to either the advancing or retreating side [27].

2.3. Tool performance evaluation

Friction stir welding tool wear is a critical issue for aluminium matrix composites, which occurs as a result of friction, rotation and movement of friction stir welding tool along the base material. Plastic deformation abrasion diffusion and reaction between the environment and the tool material are the major wear mechanism that happen in FSW tools [28]. Friction stir welding of soft metal such as aluminium and magnesium did not exhibits significant wear of the tool. However tool life issue becomes more significant when hard metals of high melting temperature or metal matrix composite (MMC) are welded by FSW. His phenomenon is characterized by the deformation and reduction in the pin diameter [29].

Figure 6 shows optical microscopy image of cross section of CY16, W-La and WC411. A crack initiated at shoulder corner and then penetrated through the pin in CY16 tool as shown in fig.6a, crack bifurcation took place during propagation and resulted in rapid fracture and chipping. Further investigation revealed that shoulder edge and shoulder-pin corner were preferred crack initiation sites, which might be due to stress concentration at these regions. Adhesion occurred between Ti-6Al-4V and CY16 as shown in Fig.6b. Tool material cracking under the adhesion layer suggested stress concentration caused by pulling force applied by adhered material. Plastic deformation of W-La tool was revealed by the deformed grain structure in Fig. 6c. The formation of stress induced crack at pin tip could reduce the resistance to wear. No adhesion of Ti-6Al-4V material was observed on W-La tool surface. In the WC411 tool, voids are nucleated at shoulder surface and shoulder corners as shown in Fig. 6e and void coalescence happens due to localized strain. Adhesion layer of Ti-6Al-4V material was also observed on the surface of WC411 tool as shown in Figure 6 [30].

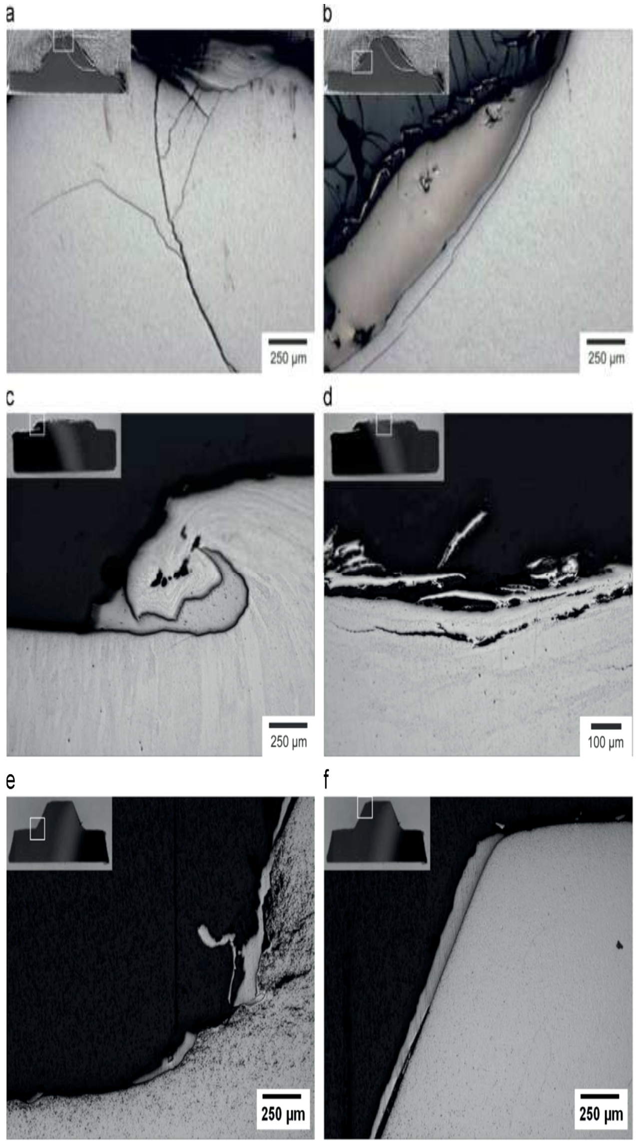

Fig. 6. Optical microscopy images of cross sections of (a, b) CY16, (c, d) W-La, and (e, f) WC411 tools. The inset at left-top corner of each figure. Shows a low magnification image [30]

There was a linear relationship between the wear rate and tool rotation speed. However, as a result of filling threads by base materials the initial wear of the tool can be delayed by the reduction of rotation speed and increase in transverse speed and after a period of time the wear rate becomes constant as shown in Fig. 7. They concluded that the self-optimized tool shape was evolved as a result of complex solid state flow of the base material during friction stir welding. Moreover, they indicated that homogenous structure could be achieved with a worm pin [31].

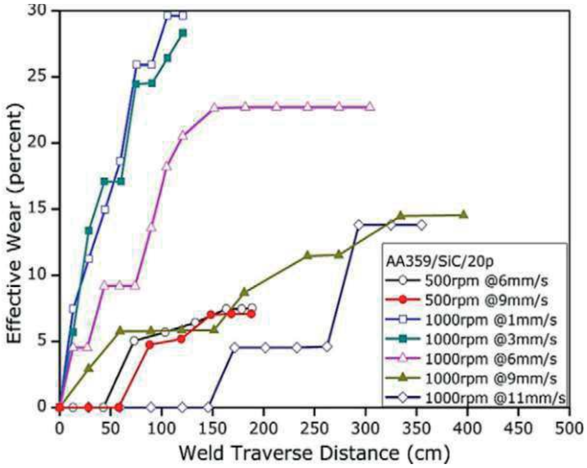

Fig. 7. Pin tool wear as a per cent of initial tool shape projections versus weld traverse [29]

2.4. Fatigue life evaluation

Friction stir processing improved the fatigue life of aluminium alloy Al-7Si-0.6Mg. FSP eliminate the porosity and refined the Si particles. The crack growth rate dropped due to elimination of the notch effect together with increased crack path tortuosity. The particles/matrix interface was responsible for crack nucleation in the FSP condition, size ratio analysis of the respective defect matches will with the Paris crack growth equation. As oscillatory crack growth behaviour was seen up to 450 µm for the cast condition, whereas in the FSP condition this behaviour stopped at 180 µm. The crack growth rate was found to be one order of magnitude higher in the cast condition than the FSP condition. Short crack behaviour was observed in both condition and the critical transition crack length matched will with the respective micro-structural characteristics dimension. The cast fatigue specimen showed a life of 45500 cycles. As expected crack were noted to have originated at porosity when the test was stopped after the first 5000 cycles which implies a 10% or lower crack initiation periods [32]. Cast A356 alloys prepared by FSP were subjected to fatigue investigated. Fatigue life improvement was attributed to significant refinement, homogenization of the microstructure and the elimination of porosity. FSP resulted in a significant breakup and uniform distribution of Si particles in the aluminium matrix as well as elimination of porosity. This lead to an improvement in fatigue stress threshold stress > 80% in the stir zone of the FSP sample. This improvement in fatigue properties is attributed to an increased effect crack length and reduction in crack growth rates. FSP can be used as a tool to locally modify the micro structures in regions experiencing high fatigue loading and thus significant improve the overall performance of aluminium casting [33]. The friction stir welding (FSW) process, has been successfully applied to several aluminium alloys, leading to joint properties (such as tensile strength, toughness, and fatigue life) in some cases higher than those of the base material [34-40]. Low cycle fatigue life of the friction stir welding composite was always lower than that of the base material, high values of total strain amplitude were characterized by a fatigue life ratio around 1:2. The lower fatigue life of the FSW material could be related to the microstructural and surface modification induced by the process, which also led to a reduction of hardness and tensile strength.

The effect of surface finishing was particularly high for the two specimens tested at the lowest strain amplitude values, which gave premature failures starting from the high geometrical discontinuity between the base material and the shoulder in the retreating side of the welding (Fig. 8 (a)) with increasing the strain amplitude this effect was of lower entity, but failure occurred in the retreating side welded zone (Fig. 8 (b)-(c)). The possible presence of residual stresses due to the welding process should not have any influence on fatigue life in strain controlled test [41].

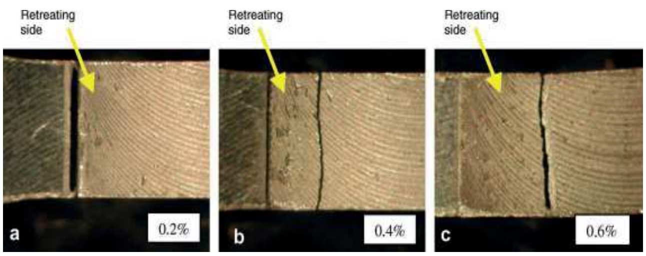

Fig. 8. Fracture appearance of FSW low-cycle fatigue specimens tested at different strain-amplitudes [41]

2.5. Effect of welding parameter

Recently many studies have been conducted to establish the optimum parameter for friction stir welding of dissimilar aluminium alloys and to identify their micro-structures, mechanical properties and defect formation. It is important to note that for FSW of dissimilar material, addition parameters, such as material arrangement and position of tool plunge with respect to the weld centre line, need to be considered, as well as general parameter such as tool geometry, rotation speed and welding speed. Because material flows and thermal hysteresis differ between the advancing and retreating sides, so material arrangement and tool plunge position exert a significant effect on weld formation. In friction stir welding process, the welding parameter including tool rotation speed, traverse and axial force affect the friction heat generation and mixing process. Therefore optimum welding parameter must be selected in order to produce the best joint strength. The efficiency of aluminium matrix composite weld joints is generally in the range of 60% to 97% of those of the base material. It is accepted that the ultimate tensile strength of friction stir welding joints of aluminium matrix composite increases by increasing the rotation speed until a specific limit [42-48].

The highest hardness value occurs in the centre of the nugget zone followed by a gradual decrease across the thermo-mechanically affected zone (TMAZ) and Heat affected zone (HAZ) until reaching the hardness value of the base material as shown in Figure 9. This is attributed to more grain refinement in the nugget zone due to dynamic recrystallization and more uniform distribution of finer reinforcement particles in the weld zone due to friction stir welding action. It may also be concluded that lower heat input leads to the formation of coarse grains because of incomplete recrystallization and thus a reduction of the nugget zone micro hardness [44].

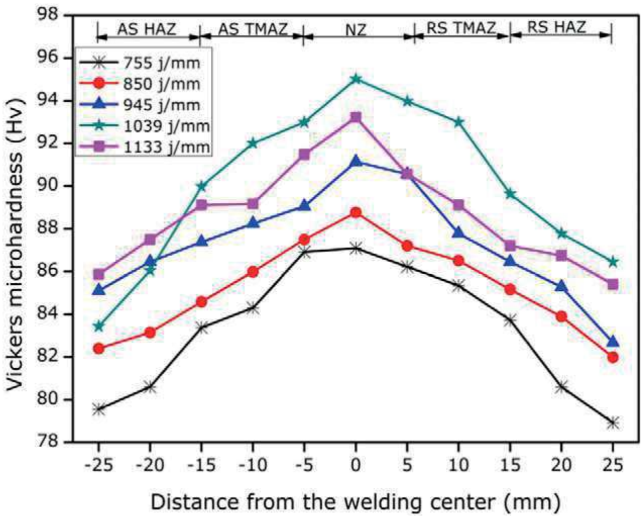

Fig. 9. Micro hardness profile across the weld region of AA6061/SiC/10p at different heat [44]

3. Conclusion

The mechanical properties of welded joint by friction stir welding are largely dependent on the combined effect of both the composition of alloying element and processing parameter, there for, the mechanical performance of friction stir welding joint should be evaluated accordingly. Past researcher showed that FSW is a potential welding process to achieve defect free joint. Welding parameter such as tool rotation, transverse speed and axial force have a significant effect on the amount of heat generated and strength of FSW joints. Microstructure evaluation of FSW joints clearly shows the formation of new fine grains and refinement of reinforcement particles in the weld zone with different amount of heat input by controlling the welding parameter.

This review aims to outline the current working on friction stir welding with number of specific issue including welding parameter, different aluminium alloy, macro and microstructure, mechanical properties, tool wear and fatigue evaluation. Friction stir welding have a potential benefits in cost reduction, joint efficiency improvement and high production accuracy make it more attractive for non weldable series. The welding parameter such as traverse speed, tool rotation speed and axial force have a significant amount of heat generation and strength of friction stir welding joints. The microstructure calculation of FSW joints clearly shows the formation of new grains and refinement of reinforcement particles in the weld zone with different amount of heat input by controlling welding parameter. The welding parameter also affect the mechanical properties of FSW joints. The wear of FSW tools is a main issue when joining different material with the help of friction stir welding, the life of welding tool could be more, when we use correct processing parameter for different material and working conditions.

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