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Mechanical and microstructure characterization of friction stir welding for dissimilar alloy- A Review

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Abstract

Friction stir welding (FSW) is a relatively new solid state joining process that uses a non-consumable tool to join two different materials without melting the workpiece material. Heat is generated by friction between the rotating tool and the workpiece material. This joining process is energy efficient, environment friendly and versatile. 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.

Keywords: Friction stir welding, Microstructure, Strength, Aluminum alloy

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. Efficient joints in terms of strength of aluminum 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, aluminum matrix composites may be selected as an alternative to high strength aluminum alloys in aero engines and aerospace structures like fins, wing and fuselage. In 2001 NASA used composite aluminum AL-Li 2195 rather than aluminum 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].

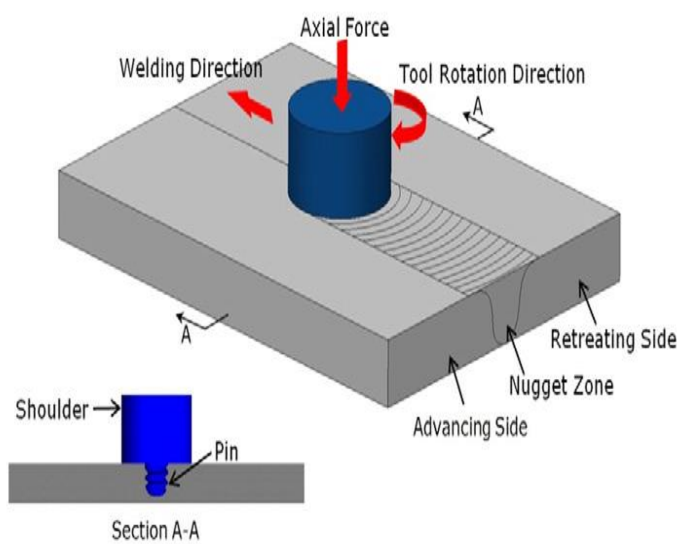

Figure 1: Friction Stir welding

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2. Literature Review

Various material which is used in nuclear , aerospace, automobile industries have been joined by various conventional welding technologies, such as gas tungsten arc welding, electron beam welding, plasma arc welding and laser beam welding. Recently, FSW technique, which could avoid the problems associated with the melting and solidification in fusion welding methods such as brittle cast structure, large distortion and residual stress, has been applied to Ti alloys, especially to the most widely used Ti–6Al–4V alloy

2.1 Microstructure

Microstructure is the very small scale structure of a material, defined as the structure of a prepared surface of material as revealed by a microscope above 25× magnification [5]. Samples of different cross section under different processing parameters are shown in Fig. 2. The stir zones are clearly visible, and, all the three rotation rates produced defect-free processed zones at the tool traverse speed of 1 IPM. With the increase in tool travel speed, processing defects started to form at the bottom of the SZ. At the condition of 2 IPM, processing defect can only be seen in the sample processed at 800 RPM. With further increase in the traverse speed to 4 IPM, small cavities were detected even in the samples at 1000 RPM, as shown in Fig. 2.In the processing condition of 900 RPM/4 IPM, there was incomplete penetration and deformation of the tool tip, because the tool travel speed was too fast and the overall process time was insufficient to heat, soften, and flow the workpiece material adequately [6].

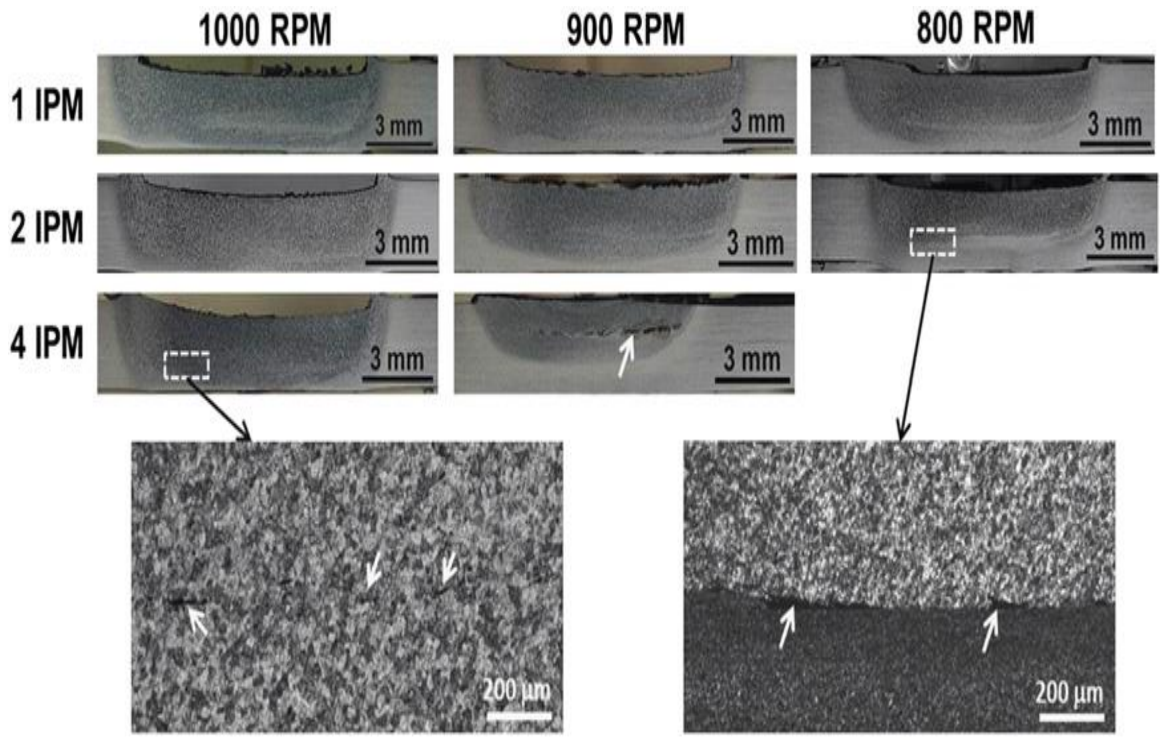


Figure. 2. Cross-section macrographs of FSP Ti–6Al–4V samples processed at different combinations of tool rotational speed (RPM) and tool traverse speed (IPM). Note thatthe processing defects are marked by white arrows [6].

Fig. 3 shows the optical micrographs from the center of the Stir zone in the processed samples. The microstructures in the Stir Zone are characterized by a fully β transformed structure in the form of lamellar α/β structures. This suggests that the peak temperatures in the SZ exceeded the β-transus temperature during processing, and β→α+β phase transformation occurred during cooling at all the performed processing conditions. However, the prior β grain size is significantly influenced by the processing parameters. It is known that β grain growth is rapid in the β phase field because of high temperature and absence of second-phase particle to impede grain boundary motion. The prior β grain size depends on the temperature and exposure time above the β -transus temperature, which are controlled by the processing parameters. Increase in tool rotational rate and decrease in traverse speed can produce higher processing peak temperature and longer exposure time at high temperature, resulting in larger prior β grain in the SZ. In the present study, the prior average β grain sizes, which are measured by the linear intercept method, are approximated to be 38, 32, 27, 25, 21, 12, 20 and 17 mm for the processing conditions of 1000 rpm/1 ipm, 1000 rpm/2 ipm, 1000 rpm/4 ipm, 900 rpm/1 ipm, 900 rpm/2 ipm, 900 rpm/4 ipm, 800 rpm/1 ipm and 800 rpm/2ipm, respectively[6].

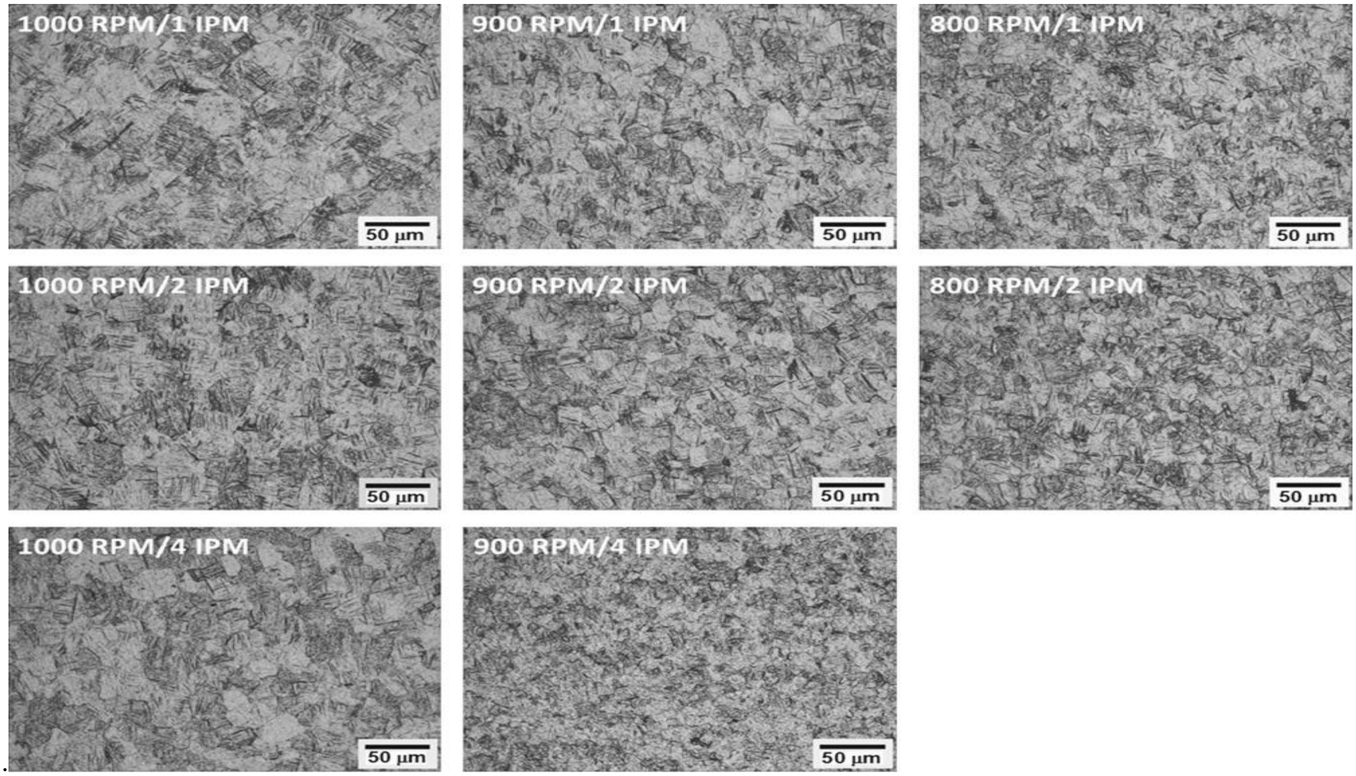


Figure 3: Optical micrographs taken from center of the SZ in the samples with different processing parameters [6].

The microstructure of the extruded sample was characterized by predominate low angle grain boundaries with gain alignment along the extruded direction and with non-uniform grain size (Fig. 4a). For the friction stir processing sample, the microstructure was characterized by uniform and equiaxed recrystallized grain with predominant high angle grain boundaries (Fig. 4b) and an average grain size of 0.7 µm. A high density of Al_3Zr disperiodds with size ranging from 5 to 20nm were uniform distributed in the aluminum matrix (Fig. 4c) [7].

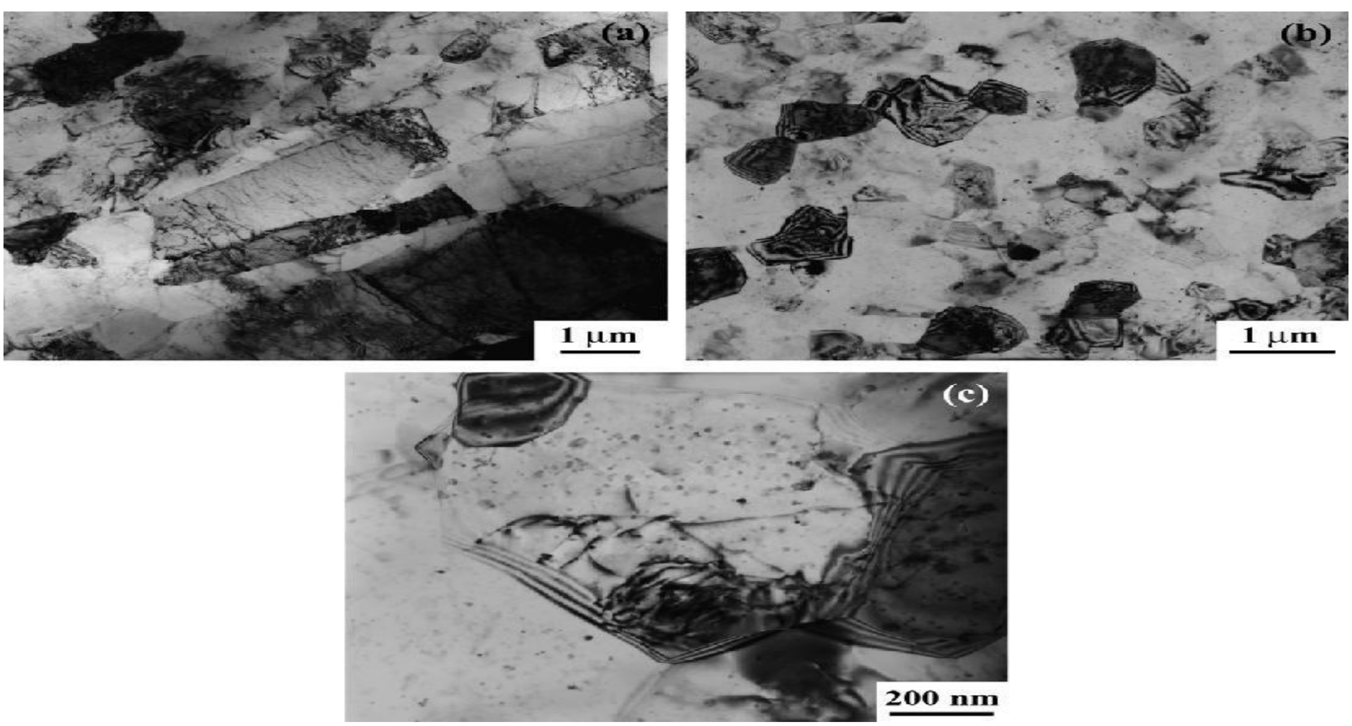


Figure 4: TEM images showing grain structure and dispersoid distribution in (a) as-extruded Al-Mg-1Zr, (b) & (c) FSP Al-Mg-1Zr [7]

FSW produces four distinct regions within the microstructure that exhibit different properties and mechanical performance. These regions are the base metal (BM), heat affected zone (HAZ), thermo-mechanically affected zone (TMAZ), and the weld zone (WZ). The HAZ typically shows evidence of heating without plastic deformation resulting in grain growth and over-aging of strengthening particles, while the TMAZ experiences plastic deformation and elongation of the grains as they are extruded around the tool. The severe plastic deformation and heating that occurs in the WZ results in a recrystallized deformation structure to produce fine, equiaxed grains [8-9].

The macrostructural and microstructural levels can have immense affects upon the mechanical performance as well. It was observed through the stop-action technique of leaving the weld tool in the material in order to observe the macroscopic flow of material around the tool, that gaps are created in the material around the threads of the tool pin [10]. Most of the time, these gaps close again once the tool has passed by, however the presence of hard particles can disrupt the material flow and cause the gaps to remain open, leaving large voids. Micro-cracks induced by post-weld cooling and porosity can also be present, although typically to a much lower degree than in fusion welds. The presence of zinc (Zn) from the use of galvanized steels can have varying effects. The bonding of Mg-steel dissimilar lap friction stir welds, since Mg and iron (Fe) are not soluble in either their solid or liquid states [11]. However, if the temperature during Friction stir welding is high enough to cause the zinc to melt, it can cause regions of porosity to form [12]. In dissimilar alloy combinations in which solid solubility can be achieved, such as with aluminum-steel welds, it may be beneficial to use alloys which are not zinc-coated.

Figure 5: Macrographs showing nugget and transitional zones of 5-pass FSP A356 [13]

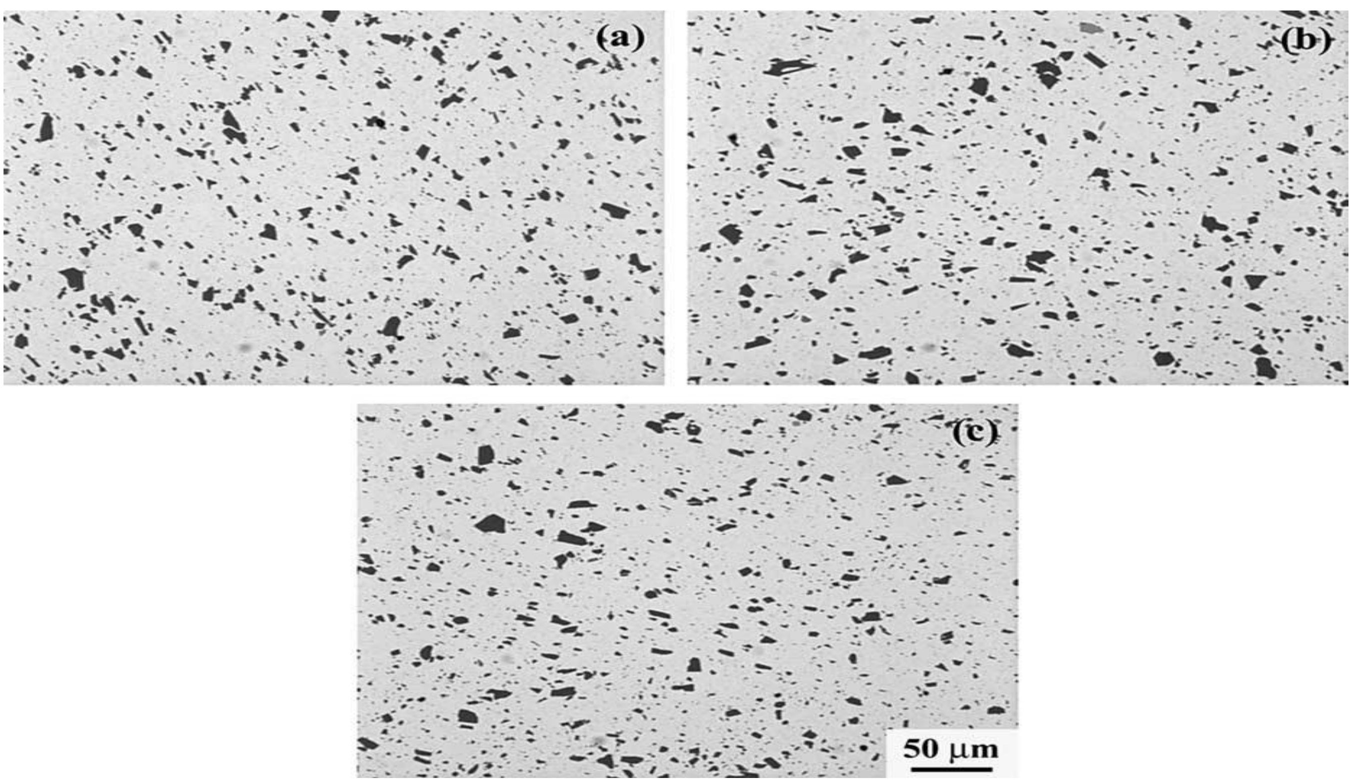


Figure 6. Typical optical micrographs showing Si particle distribution in 5-pass FSP A356: (a) 1st pass, (b) 2nd–3rd pass transition, and (c) 5th pass (locations A, D, and I in Fig. 5) [13]

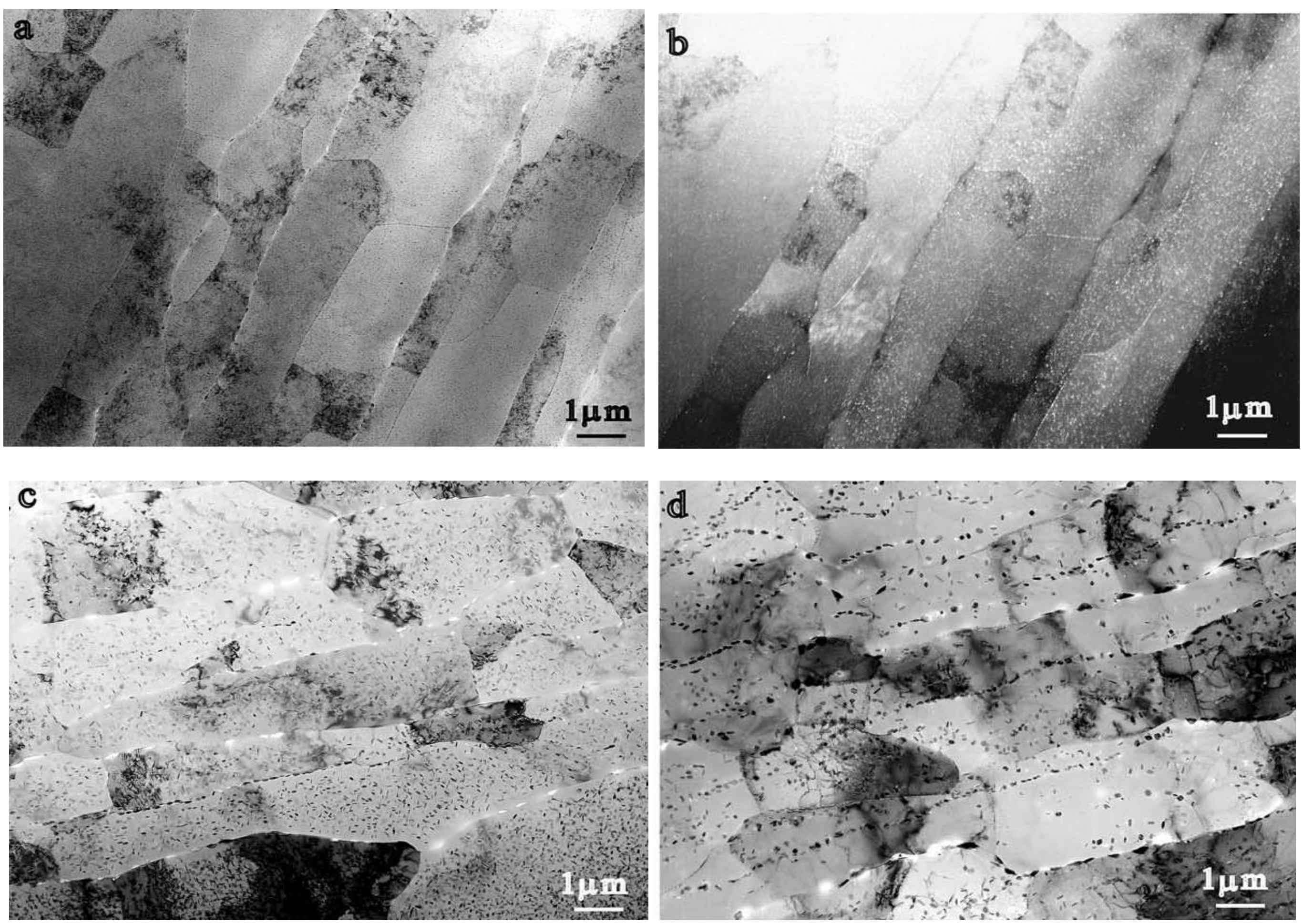
Fig. 6 show that the size and aspect ratio, as well as the distribution of the Si particles, are quite similar in various microstructural regions of the 5-pass FSP A356 sample. Thus, the difference between the tensile properties of the transitional and nugget zones cannot be attributed to the Si particles. The reason for the slight reduction in strength in the transition zones is not clear. One possibility is that the strengthening precipitates, Mg Si, in the transition region go through additional coarsening [13].

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 transverse 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 [14, 15].

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 aluminum 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 [16-19].

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 [20].

The grain structure in the base metal and weldment are shown in low magnification transmission electron microscopy (TEM) photo graph as shown in fig.7. 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. 7a). The small difference in diffraction contrast between neighboring grains in the dark field image shows the dominance of low angle boundaries (Fig. 7b). 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.7c). 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. 7d) [21].



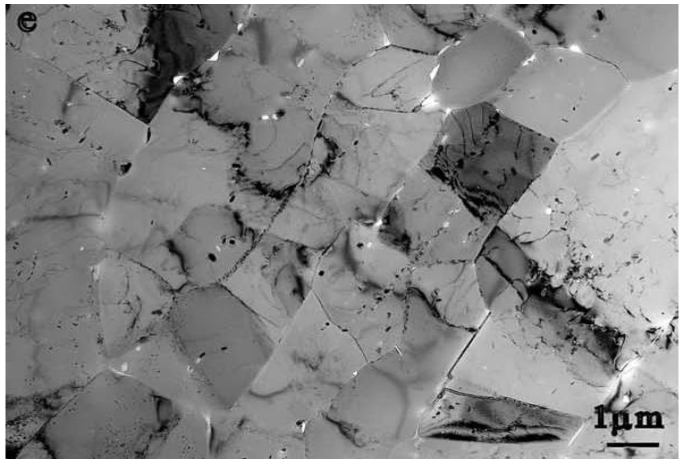


Figure 7: Grain structure in different weld regions: (a) base metal, (b) dark field image of region (a), (c) HAZ, (d) TMAZ I, (e) TMAZ [21]

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 Friction Stir Processing multiple times.

Fig. 8a 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.8b, 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. 8c. The typical grain structure of the FSPed nugget is shown in Fig. 8d. The grains were mostly equiaxed, although in a few instance some grains aligned parallel to either the advancing or retreating side [22].

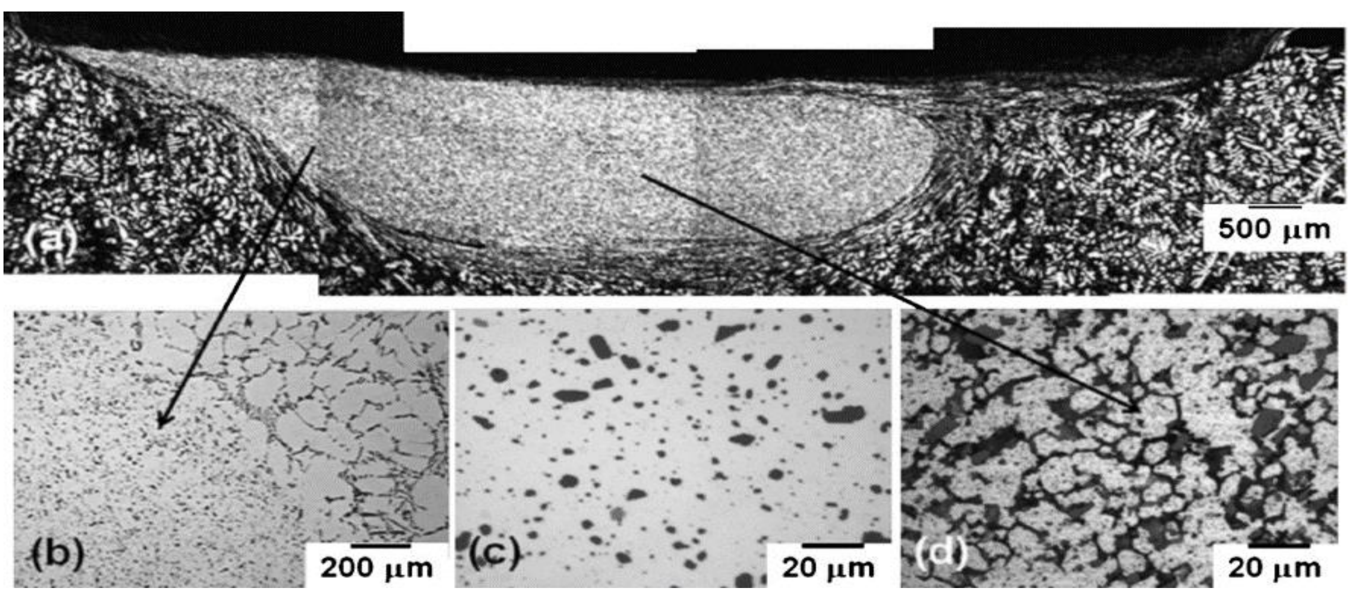


Figure 8: (a) Cross-section optical macrograph of a single pass run, (b) interface between cast and FSPed region showing extent of particle refinement, (c) higher magnification image shows size and shape of Si particles inside the FSPed nugget and (d) grain structure inside the nugget [22]

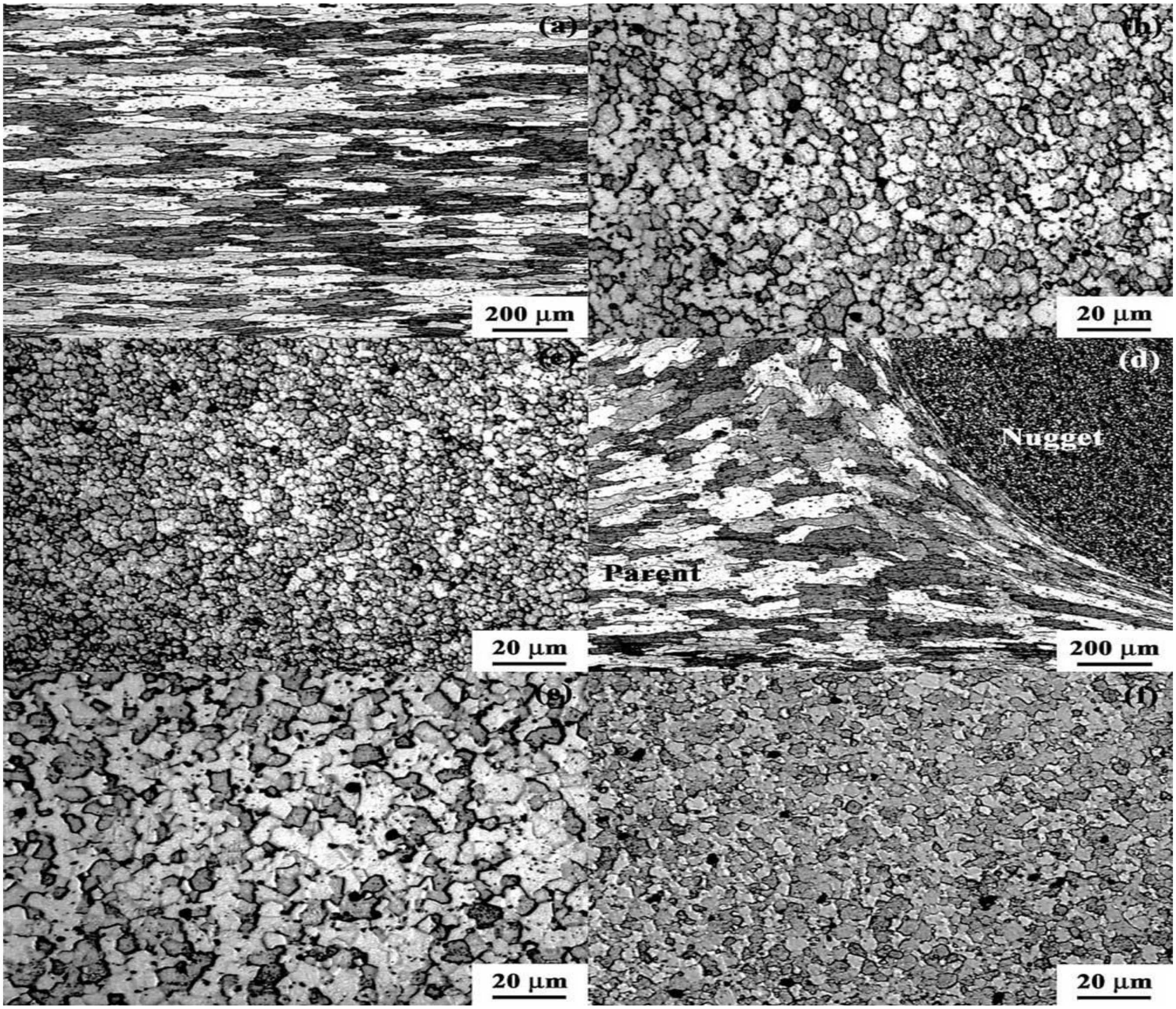


Figure 9: Optical micrographs showing grain structure of (a) parent zone, (b) FSP zone, 4 ipm/400 rpm, (c) FSP zone, 6 ipm/350rpm, (d) transition zone, 4 ipm/400 rpm, (e) FSP zone, 4 ipm/400 rpm after heat treatment at 490 °C/1 h, and (f) FSP zone, 6 ipm/350 rpm after heat treatment at 490 °C/1 h [23]

The microstructural changes in 7075Al following both FSP parameter sets and the post-FSP heat treatment are shown in fig. 9. The parent metal microstructure consisted of large elongated pancake shaped grains typical of a hot rolled structure (Fig. 9a). In the stirred zone, the microstructure was characterized by fine and equiaxed grains (Fig.9b and c). The average grain size was 7.5 and 3.8 µm for processing parameters of 4 ipm/400 rpm and 6 ipm/350 rpm, respectively. The transition zone between the parent material and stirred zone was characterized by a highly deformed structure, Fig. 1d. The parent metal elongated grains were deformed in an upward flowing pattern around the fine grain zone. Although the transition zone underwent plastic deformation, recrystallization did not occur in this zone. After heat treatment at 490 °C for 1 h, grains in the FSP zone coarsened slightly (Figs. 9e and f). The mean grain size increased to 9.1 and 5.9 µm for the two FSP conditions of 4 ipm/400 rpm and 6 ipm/ 350 rpm, respectively. This demonstrates relatively stable grain growth in the fine grain microstructure locations. Such a fine and stable microstructure is suitable for superplastic deformation and forming at high temperature [23].

2.2 Mechanical Properties

2.2.1 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 aluminum alloy. Defect free welds with good mechanical properties have been made in a wide variety of aluminum alloys, thickness from 1 mm to more than 35 mm is unweldable. In addition, friction stir weld can be accomplished in any position. [24-30].

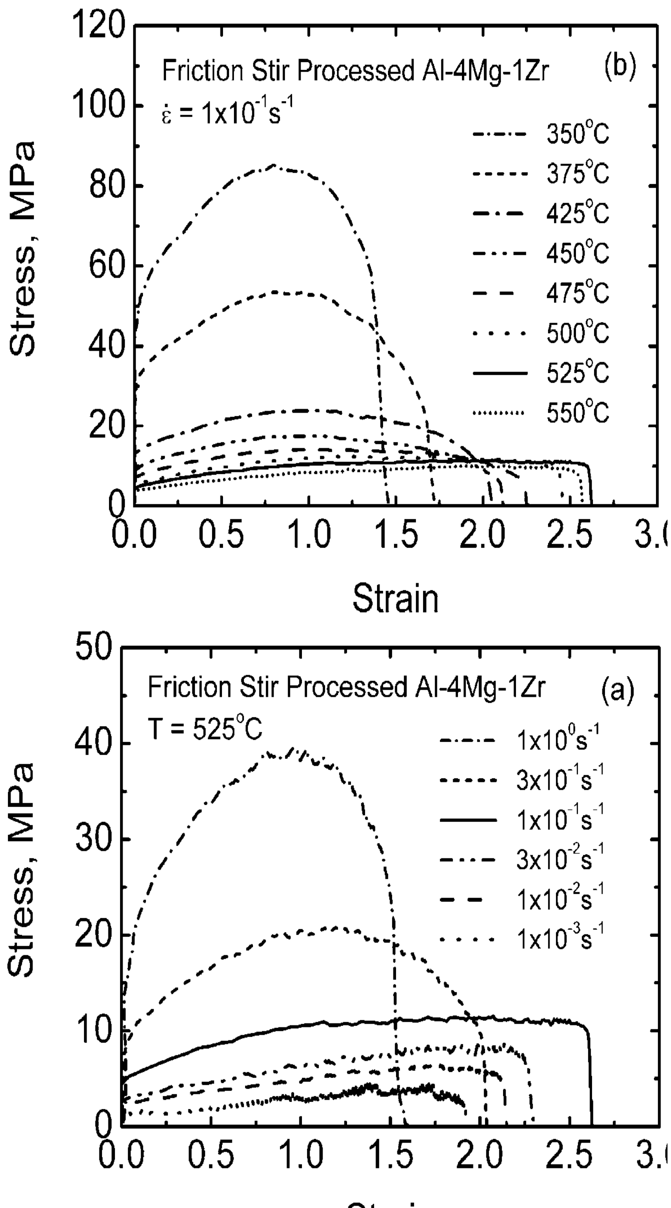


Figure 10: Stress strain behavior of friction stir processing Al-4Mg-1Zr, (a) initial strain rate at 525^{0}C, (b) temperature at an initial strain rate 1x10^{-1} s^{-1} [33]

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 behavior of carbon steel the value of pre-stress and thermal stress should be low as possible [31-32].The stress strain behavior of friction stir processing Al-4Mg-1Zr as shown in fig. 10. The optimum strain rate for maximum elongation at 525^{0}C was 1x10^{-1}s^{-1}. This show that high strain super plasticity can be achieved in the Al-4Mg-1Zr alloy by FSP [33].

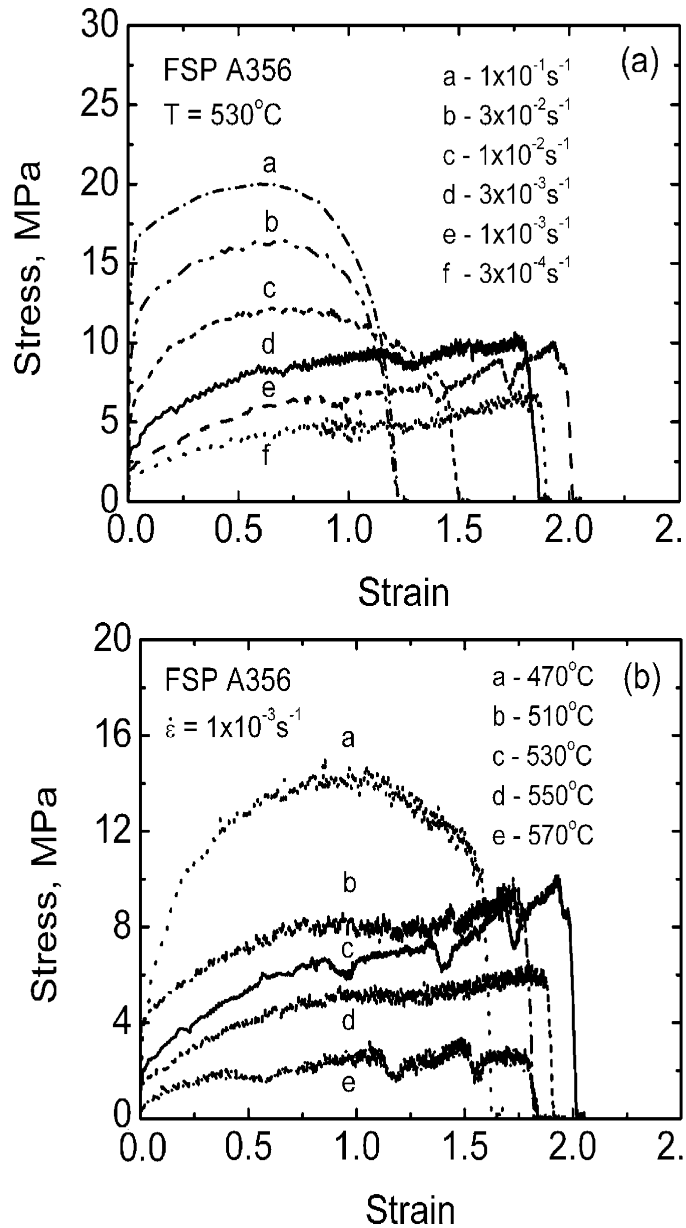


Figure 11: Stress–strain behavior of FSP A356 as a function of (a) initial strain rate at 530^{0}C and (b) temperature at an initial strain rate of 1x10^{-3} S^{-1} [34]

The stress–strain behavior of FSP A356 is shown in fig. 11 as a function of initial strain rate and temperature. Clearly, FSP samples exhibited superplastic behavior. The optimum strain rate for maximum elongation at 530^{0}C was 1x10^{-3}s^{-1}. At an initial strain rate of 1x10^{-3}s^{-1}, the optimum temperature for maximum elongation was 530^0C [34]. Generally, the stress–strain curves of FSP A356 exhibited significant strain hardening. This is consistent with that in FSP 7075Al and Al–4Mg–1Zr. The strain hardening during superplastic flow is generally attributed to concurrent grain growth [35-36].

Fig. 12a and b show a comparison of elongation for both the FSP and cast conditions as a function of strain rate and temperature. Elongation of the cast A356 was low (<200%) and did not exhibit any appreciable dependence on strain rate or temperature. By comparison, FSP A356 exhibited a maximum elongation of 650% and demonstrated a strain rate and temperature sensitivity with optimum test parameters of 530^0C at an initial strain rate of $1x10^{-3}s^{-1}$[34].

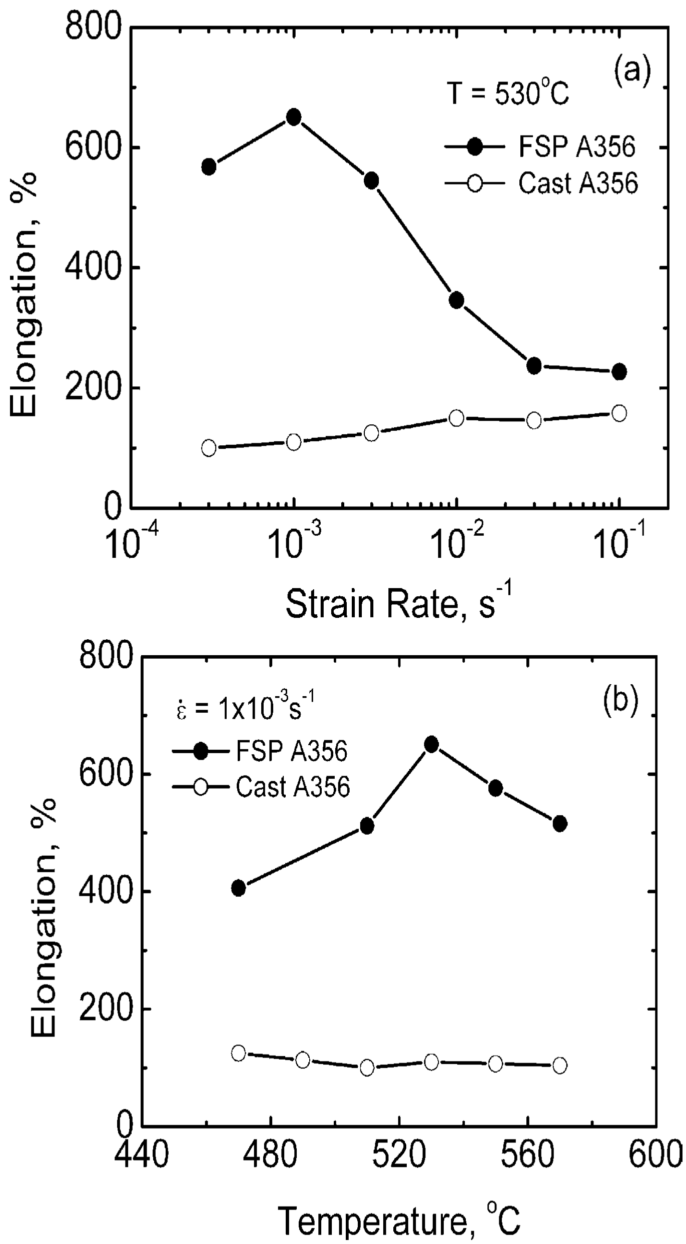


Figure 12. Variation of elongation with (a) initial strain rate and (b) temperature for both FSP and cast A356 [34].

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. 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 [37-38].

2.2.2 Effect of Welding parameter

Recently many studies have been conducted to establish the optimum parameter for friction stir welding of dissimilar aluminum alloys and to identify their microstructures, 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 center 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 aluminum 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 aluminum matrix composite increases by increasing the rotation speed until a specific limit [39-45].

3. Conclusion

In this review the 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. 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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