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Friction Stir Processing of Aluminum alloys for Defense Applications

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ABSTRACT

Friction stir processing (FSP) is a surface modifying Technique, which was developed, based on the basic principles of friction stir welding (FSW), but FSP is used to modify the local microstructure and does not join metals together. A rotating tool with pin and shoulder is inserted into a single piece of material and traversed along the desired path to cover the region of interest. Friction between the shoulder and workpiece results in localized heating which raises the temperature of the material to the range where it is plastically deformed. During this process, the severe plastic deformation and thermal exposure of material, results in a significant evolution in the local microstructure. FSP has been successfully used for formation of nanograin, increase the surface hardness and also enhances the wear resistance, tensile strength and fatigue strength of the material. This review paper, the current scenario and development of FSP of various materials mainly (a) formation of nanograins, microstructure and mechanical properties. (b) Effect of FSP/W process parameters.

Keywords Friction Stir Processing; Aluminium Alloys; Process Parameters.

1.0 Introduction

FSP was developed by Mishra et al, 6 for improving the surface modification based on the principles of new solid state welding Technique. In this process a special non consumable rotating tool is used; the shoulder of the tool rubs the surface and gives enough load and generating sufficient heat to soften the material. The pin plunged in to the material producing refined microstructure due to „stirring“ action. The purpose of this article is to review the process parameters and tools used in FSP/W of ferrous materials and Al/Mg Alloys. The advantages using FSP are as follows

1. It is used to transform a heterogeneous microstructure to homogeneous, refined microstructure.
2. It is used to form nanostructure surface as a result increases the hardness of the base metal.
3. To improve the tensile properties, fatigue properties and wear characteristics of the surface material.

During FSP no gases involved, no smoke is produced, no secondary materials are used, due to this reason it is called “green-efficient technology” and it not changes the size and shape of the processed components. FSP can be accurately described as a forging and extrusion, or metal working process. The resulting microstructure is composed three primary zones the heat-affected zone (HAZ), the thermo-mechanically-affected zone (TMAZ), and the nugget zone (NZ). As a result of intense plastic deformation at elevated temperature, grain refinement to a size range from 0.8 to 12 μ m can be achieved. It is well known that the nugget zone consists of fine and equiaxed grains produced due to the dynamic recrystallization. FSP has proven to be successful in the modification of various properties such as formability, hardness, and yield strength, fatigue and corrosion resistance. The current developments in process modelling, microstructure and properties, material specific issues, applications of friction stir processing have been discussed in detail. Because Tool geometry is very important factor for producing sound welds and it is known that a cylindrical

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threaded pin and concave shoulder are widely used welding tool features.. Processing parameters, including tool rotation rate, traverse speed, spindle tilt angle, and target depth, are crucial to produce sound and defect-free processed region. It has been suggested by some researchers that FSP can be generally described as an in situ extrusion process and the stirring and mixing of material occurred only at the surface layer of the processed zone adjacent to the rotating shoulder. FSP results in significant temperature rise within and around the weld. A temperature rise of 400–500°C has been recorded within the stirred zone for aluminium alloys. Intense plastic deformation and temperature rise result in significant micro structural evolution, i.e., fine recrystallized grains of 0.1–18 μm, texture, precipitate dissolution and coarsening, and residual stress with a much lower magnitude.

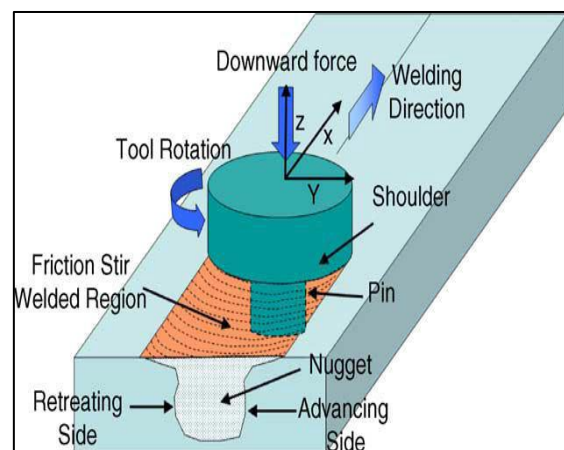
Three different micro structural zones have been identified in friction stir processed region, i.e., nugget region experiencing intense plastic deformation and high-temperature exposure and characterized by fine and equiaxed recrystallized grains, thermo-mechanically affected region experiencing medium temperature and deformation and characterized by deformed and un-recrystallized grains, and heat-affected region experiencing only temperature and characterized by precipitate coarsening. FSP exhibits a considerable improvement in strength, ductility, and fatigue and fracture toughness.

FSP has found several applications for micro structural modification in metallic materials, including micro structural refinement for high-strain rate super plasticity, fabrication of surface composite on aluminium substrates, and homogenization of microstructure in nano phase aluminium alloys, metal matrix composites, and cast Al–Si alloys. Despite considerable interests in the FSP technology in past decade, the basic physical understanding of the process is lacking. Some important aspects, including material flow, tool geometry design, wear of welding tool, micro structural stability, welding of dissimilar alloys and metals, Friction stir processing is a novel surface modification technique and resulted in significant grain refinement in Aluminum alloy.

The microstructure is characterized by equiaxed fine grains with well-defined grain boundaries. The microstructure evolved through

dynamic recovery and dynamic recrystallization process. The strength of the FSP material improved significantly and at the same time the ductility was also retained, the hardness also improved substantially. FSP was found to be beneficial in improving wear resistance. The high wear behavior in the stir zone is attributed to a lower coefficient of friction and the improved micro-hardness in this region.

Fig 1: Working Principle of Friction Stir Processing (Mishra⁶)



2.0 Literature Review

L. Karthikeyan, V. S. Senthil Kumar¹ discussed the relationship between process parameters and mechanical properties of friction stir processed AA6063-T6 aluminium alloy plate in T6 temper condition was single pass FSP. Processing was carried out at different axial forces (8, 10 and 12KN), tool feeds (22.2, 40.4 and 75 mm/min) and tool rotational speeds (800, 1000, 12000, 14000 and 16000 rpm). And found that at lower axial forces, friction stir processed material exhibits lower tensile and ductility properties and . on increasing the axial force, they attain peak values but fall with further increases.

The depth to which the tool pin plunges into the process zone and the accompanied material flow is controlled by the shoulder force, which in turn is influencing by the axial force. And also found that

Lower axial forces result in both poorer stirring as well as insufficient consolidation of material. Besides the insufficient downward force

result in absence of vertical flow giving rise to defects and reduced tensile and ductility properties. And concluded that by increase in axial load increases the heat input and reducing flow stress due to the pressure developed to consolidate the material in process zone. He is found that very high axial forces lead to higher than optimal temperatures which causing excessive thinning of material accompanied by micro voids and tunnel

defects due to excessive heat input. As increase of approximately 46.5% compared to parent material in the tensile strength of specimens processed at an axial force of 10KN, tool feed of 40.2 mm/min and a tool rotational speed of 1400 rpm and also found that ductility increases in the processed specimens ranged from 3% to 133%. And hardness followed the same trend as that of tensile properties. In his experiments, all the specimens processed with an axial force of 8KN yielded process defects and multivariate non linear regression equations are used to predict the mechanical properties such as yield, tensile, ductility and micro hardness. In the multivariate case, with more than one independent variable, regression line is articulated as a function of axial force, tool feed and the tool rotational speed. A second order polynomial curve is found to best fit the experimental values. K. Elangovan, V. Balasubramanian 2. did experiments on for finding the Influences of tool pin profile and tool shoulder diameter on the formation of friction stir zone in rolled plates of 6mm thickness AA6061 aluminium alloy cut into 300x150 mm were prepared in butt joint configuration and followed single pass welding procedure with high carbon steel tool for five different tool profiles (i.e. cylindrical, threaded cylindrical, tapered cylindrical, square, triangle) and each profile with three different shoulder diameters (15, 18 and 21mm) is employed for fabricating 15 joints. They considered welding parameters (i.e. rotational speed of 1200rpm, weld speed of 1.25mm/s and axial force of 7KN and tool dimensions (i.e. 5.5mm pin length and 6mm pin diameter in the experiments and joints were fabricated by square pin profiled tool exhibited superior tensile properties irrespective of tool shoulder diameter and triangular pin profiled tool fabricated joints showed almost matching tensile properties and rest profile tools produced inferior joints. The flat faces of profiles were associated with eccentricity which allowed

incompressible material to pass around pin profile and triangular and square pin profiles produce a pulsating stirring action in flowing material, about 80 pulses/s for square pin and 60 pulses/s for triangular pin with 1200 rpm. This pulsating action yields very fine equiaxed microstructure with high hardness and strength. The joints fabricated by tools with shoulder diameter of 18mm have shown higher tensile strength and elongation and this trend is common for all tool pin profiles. In their experiments, the tool shoulder diameter is having directly proportional relationship with the heat generation due to friction and larger shoulder diameter leads to wider contact area and hence the wider TMAZ and HAZ subsequently deteriorating tensile properties of the materials. They found the less shoulder diameter resulted in less heat generation and hence weld metal consolidation is not good in FSP region. With optimum diameter of 18mm, the fabricated joint consisted of fine equiaxed grains with uniform distribution of fine strengthening precipitates throughout the matrix causing higher tensile strength and hardness and 15 joints were fabricated using square pin profiled tool with shoulder diameter of 18mm showed superior tensile properties. K. Elangovan, V. Balasubramanian 3. did experiments for finding the Influence of tool pin profile and welding speed on the formation of friction stir processing zone They used rolled plates of 6mm thickness AA2219 aluminium alloy cut into 300 x 150 mm in butt joint configuration. Single pass welding procedure normal to rolling direction was followed with high carbon steel tool. five different tool profiles (cylindrical, threaded cylindrical, tapered cylindrical, square, triangle), each with three different welding speeds (0.37, 0.76 and 1.25 mm/s) were employed to fabricate 15 joints and welding parameters like rotational speed of 1600 rpm and axial force of 12kN with used tool dimensions like 5.7mm pin length and 6mm pin diameter. They carried out macrostructure analysis and found the formation of defect free FSP zone is a function of tool profile and used welding speeds. In their experiments, the joints were fabricated by square tool profile exhibited superior tensile properties with joint efficiency of 61% as compared to other joints irrespective of welding speed and triangular pin profiled tool fabricated joints showed almost matching tensile properties and rest profile tools produced inferior joints irrespective of welding

speeds used and found that the flat faces of profiles are associated with eccentricity which allows incompressible material to pass around pin profile. Also triangular and square pin profiles produce a pulsating stirring action in flowing material, about 100 pulses/s for square pin and 75 pulses/s for triangular pin with 1500 rpm. This pulsating action yields very fine grained microstructure with uniformly distributed precipitates (CuAl₂) and in turn yields higher strength and hardness and found that constant rotational speed of 1600 rpm, higher welding speed resulted in lower heat input per unit length of the weld causing lack of stirring in the friction stir processing zone. Lower weld speed resulted in higher temperature and slower cooling rate in the weld zone causing grain growth and severing clustering of CuAl₂ precipitates. They also observed that the material on retreating side never enters into rotational zone but the material on advancing side form the fluidized bed near the pin and rotates around it. Hence the weld zone is heterogeneous and there is variation in flow of material on retreating and advancing sides evident with lower hardness on retreating side which is the major fracture site and 15 joints, the joint fabricated using square pin profiled tool at a welding speed of 0.76 mm/s exhibited maximum tensile strength and higher hardness- K. N. Ramesh, S. Pradeep and Vivek Pancholi⁴ studied Multipass Friction Stir Processing and its effect on Mechanical Properties of Aluminium Alloy 5086 and conducted experiments on, 6mm plates of commercial AA 5086 alloy cut into 150 mm x 110 mm were used for single and multipass FSP and non consumable hot die steel tool with flat shoulder of 24mm diameter, a cylindrical pin of 6 mm diameter and 3 mm length.

The separation between subsequent passes during multipass FSP was 3mm and 12 passes in all were carried out by them and two processing methods were employed (i) intermittent multipass processing in which the material was allowed to cool back to room temperature after each pass and (ii) continuous multipass processing in which FSP was continuously performed for 12 passes without any cooling between passes and found that the grain size increases with a traverse speed (TS) of up to 80 mm/min and then start decreasing at higher speed. up to TS of 110 mm/min, grain size obtained after CMP is coarser than IMP and single pass processing and for higher TSs,

obtained grain sizes for all processing variants lie within narrow region. The CMP material processed in initial passes at low traverse speed is exposed to a temperature of 0.3 T_m for a sufficiently long time and may cause grain growth (cause of coarse grains). In IMP, the material does not experience any preheating of the processed area and is cooled to room temperature causing comparatively finer grains, bulk properties like yield strength and UTS showing a significant reduction after multipass FSP compared to Single pass and base metal because of dissolution of precipitates.

However, hardness after single and multipass are found to be higher than the base metal as grain size is reduced. micro structural inhomogeneity caused by multipass processing is reason for decrease in strength compared to single pass and base metal. They found that the yield and ultimate tensile strength to decrease up to the traverse speed of 110 mm/min and then increase at 150 mm/min. At traverse speed of 150 mm/min, lower heat input and higher strain rate result in grain refinement and hence better strength. Ductility values are found to be better in multipass and single pass processed material than the base material under all processing conditions used. Adem Kurt, Ilyas Uygur and Eren Cete⁵ carried out work on surface modification of aluminium by friction stir processing used cold-rolled plates of 1050 aluminium alloy were used average size of the SiC particles about 10micrometers and added a small amount of methanol and mixed, and then applied to surface of the plates to form a thin SiC particle layer without any binder in the mixture. The experimental dimensions of the work piece were 50mmx100mmx5mm and AISI 1050 steel tool was made with the rotating shoulder 0.1mm inserted into the work piece. The tool was rotated clockwise at rotation speed of 500–700–1000 rpm. They kept travelling or transverse speeds of 15–20–30 mm/min and the tool spindle angle of 2°. They performed micro structural observations and vickers micro hardness test on the treated surfaces with a load of 100g on a specimen of dimension 10mmx100mmx5mm and found the effect of travelling speed was that the thickness of the modified surface significantly decreased due to the heat input. An increase in rotation speed caused thicker surface thickness compared with slow rotation

speed rates. At high travelling speed (30 mm/min), the surface composite layer SiC, was usually weakly bonded with the aluminium alloy substrate.

3.0 Experimental Results

B. Zahmatkesh⁸ observed hardness profile that on increased travelling speeds caused significant increment on the hardness values for all rotational speeds for the plain specimens and found the highest hardness value was 80 and the lowest was 37 for the plain specimens however, increased rotation speeds resulted in lower hardness values at the same travelling speeds and observed in the bend test that the plain FSP treated surface was much more ductile and had lower yield strength as compared with SiC added specimen. Three point yield strength of plain specimen was 60MPa for plain specimen, but it was 84MPa for the SiC added specimen. While analysing the processed specimen they have observed that there are three distinct regions on the microstructure

1. Upper surface where SiC particles are homogenously distributed. The thickness of this region can be adjusted by rotational and travelling speed or pin height.
2. Lower surface where extremely small fine grains, broken inclusions and redistributed fine precipitations occur as a result of recrystallization.
3. Beneath the surface where elongated grains can be seen due to the material flow caused by the rotating shoulder that includes high plastic deformation in this zone.
4. Base metal, where no micro structural changes occurred.

Fig 2. Geometry and Dimensions of the Process Tool (B. Zahmatkesh⁸)

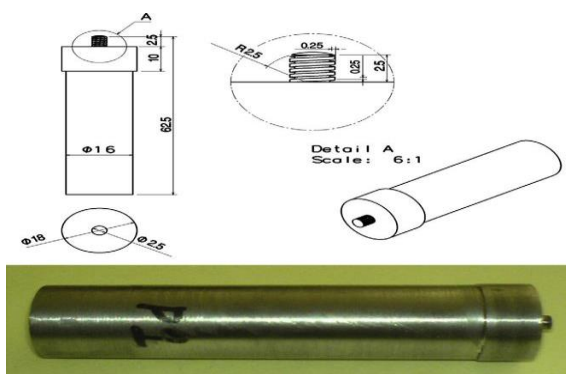


Fig 3. Optical Micrographs of Different zones of FSP Sample (a) NZ, (b) TMAZ, (c) HAZ, and (d) BM (B. Zahmatkesh⁸)

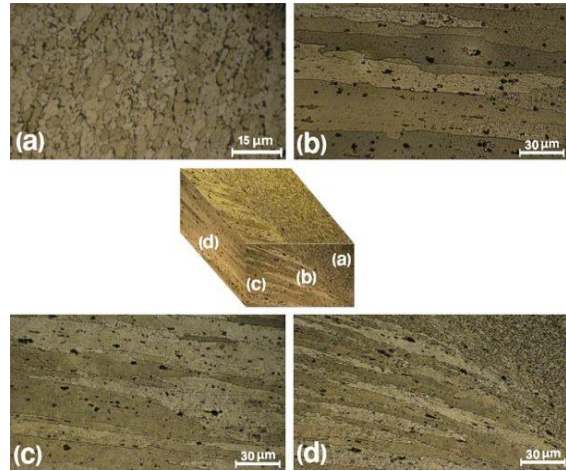
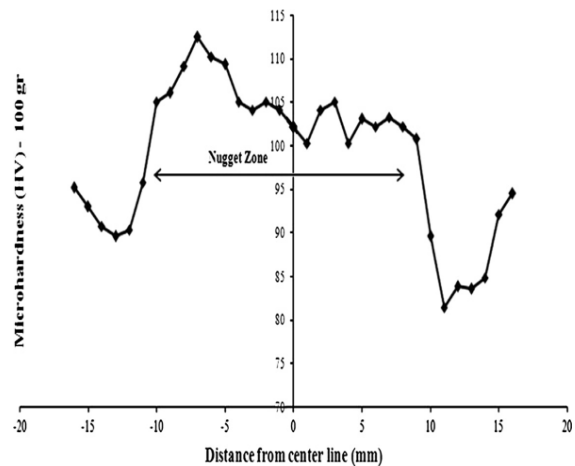


Fig 4. Micro-Hardness Profile Measured on the Cross Section of the FSP zone B. Zahmatkesh⁸



The main parameters the effect of strain rate and temperature on the nanograins and formation of ultrafine grains. The full annealed 1.5 mm thick sheet (20cmx 20 cm) IF steel is FSP by using tungsten carbide tool with 16 mm shoulder diameter without any pin. The tool angle is 30 and plunge depth is 0.5 mm. The rotational speeds (800, 1250, 1600 and 2000rpm) and two traverse speeds 31.5 and 63 mm/min were tried. The temperature during FSP was 876 to 903oc, to prevent any grain growth the work piece was quenched (mixture of ice & water at 600oc cooling rate) immediately after the FSP. The strain rate is the controlling parameter when the rotation speed increases from 800 to 1600 rpm, leading to finer grains. For increase in the rotation speed results

in strain rate as well as in higher temperature. The former leads to a reduction in grain size, whilst the latter promotes the grain growth. Chen YC and Nakata [7] studied the SKD61 tool steel by FSP using a polycrystalline cubic boron nitride. Fine grains with a marten site structure were produced in the FSP zone, which led to the increase of the micro indentation hardness. The wear width and depth of the friction stir processed zone at the load of 1.96 N were 339 μ m and 42 μ m of the base metal, decreased by 62% and 86%. His studies suggests that low heat input is an effective method to produce a FSP zone composed of relatively fine grain marten site structure with good tensile properties and wear characteristic. The 10 mm thick SKD tool steel FSP by PCBN consists of a 22mm in diameter convex shoulder a 5mm long probe. The forging load of the tool was 30KN. The rotational speeds were within the range of 200 to 800 rpm and the travel speeds were 0.5, 1.0 and 1.25mm/s. The hardness is the FSP zones is higher (890Hv) higher than that in the base metal (220Hv), which is caused by marten site transformation. The wear width and wear depth of the base metal are 888 μ m and 42 μ m respectively. After FSP the wear width and wear depth of the base metal is decreased to 339 μ m and 6 μ m respectively. The average coefficient of the FSP zone (0.73) is slightly higher than that of the base metal (0.66). It is known that by the abrasive wear mechanism, the wear of the material decreases with the increasing hardness.

4.0 Results and Discussions

Current developments in process modelling, microstructure and properties, material specific issues, applications of friction stir processing have been addressed. Tool geometry is very important factor for producing sound welds. From the open literature, it is known that a cylindrical threaded pin and concave shoulder are widely used welding tool features.

Besides, tri-fluted pins such as MX TrifuteTM and Flared-TrifuteTM have also been developed. Processing parameters, including tool rotation rate, traverse speed, spindle tilt angle, and target depth, are crucial to produce sound and defect-free processed region. It has been suggested by some researchers that FSP can be generally described as an in situ extrusion process and the stirring and mixing

of material occurred only at the surface layer of the processed zone adjacent to the rotating shoulder. FSP results in significant temperature rise within and around the weld.

A temperature rise of 400–500oC has been recorded within the stirred zone for aluminium alloys. Intense plastic deformation and temperature rise result in significant micro structural evolution, i.e., fine recrystallized grains of 0.1–18 μ m, texture, precipitate dissolution and coarsening, and residual stress with a much lower magnitude. Three different micro structural zones have been identified in friction stir processed region, i.e., nugget region experiencing intense plastic deformation and high-temperature exposure and characterized by fine and equiaxed recrystallized grains, thermo-mechanically affected region experiencing medium temperature and deformation and characterized by deformed and un-recrystallized grains, and heat-affected region experiencing only temperature and characterized by precipitate coarsening. FSP exhibits a considerable improvement in strength, ductility, fatigue and fracture toughness. FSP has found several applications for micro structural modification in metallic materials, including micro structural refinement for high-strain rate super plasticity, fabrication of surface composite on aluminium substrates, and homogenization of microstructure in nanophase aluminium alloys, metal matrix composites, and cast Al–Si alloys.

Despite considerable interests in the FSP technology in past decade, the basic physical understanding of the process is lacking. Some important aspects, including material flow, tool geometry design, wear of welding tool, microstructural stability, welding of dissimilar alloys and metals, require understanding. Phases during FSP. The processing parameters exhibit significant effects on formation of surface composite layer.

1. It was observed that when the target depth is too large, the shoulder of tool pushes way all the preplaced SiC particles, and basically no surface composite is formed.
2. Too small depth was also ineffective to mix SiC particles into aluminium alloy.
3. A target depth of 2.03 mm resulted in incorporation of SiC particles into aluminium matrix.

4. The bonding of surface composite layer and substrate plate was influenced by the transverse speed. At higher transverse speed, the surface composite layer was usually separated from the aluminium alloy substrate and the bonding was poor.
 5. The surface composite layer appears to be very well bonded to the aluminium alloy substrate, and no defects were visible.
 6. With same processing parameters and increasing the amount of preplaced SiC particles, surface composite with higher particle content were generated.
 7. There are several advantages of FSP as compared to laser processing, high- energy electron beam irradiation, and casting sinter- firstly the FSP is carried out in solid state, so interfacial reaction and formation of detrimental phases are avoided, secondly, the FSP results in significant grain refinement in surface layer. Thirdly, FSP operation is relatively simple and easily controlled because no complicate high energy laser device or high- voltage electron accelerator is needed.
 8. In addition, curved surfaces can be handled by changing the tool shoulder geometry.
 9. Alternatively, the tool-spindle angle can be changed during processing to follow the surface curvature using a multi-axis computer- controlled machine with feedback loop.
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