



## New methods to enhance the mechanical characteristics of welded joints of dissimilar Al-alloys by friction stir welding

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### Abstract

The friction stir welding is a newer technique used for refining and homogenizing the grain structure of metal sheet. Friction stir processing is a great potential in the field of super plasticity and metal matrix composites. Many investigators observed that the FSW greatly enhances mechanical properties of welded joints of Al alloys. It is a solid-state welding technique which is specially designed rotating cylindrical tool that comprises of a probe and shoulder. The probe of the tool is inserted into the sheet material while rotating and the shoulder moves over the surface of the sheet, and then traverses in the desired direction. The contact between the rotating probe and the sheet material generate heat due to friction which softens the material and the mechanical stirring caused by the probe, the material within the processed zone undergoes intense plastic deformation yielding a dynamically-recrystallized fine grain microstructure. In this paper, the FSP tool pin rotates on an already welded joint by TIG welding to improve the lower the welding load and weld quality by adjusting the processing parameters of friction stir processing of different aluminum alloy.

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*Keywords:* TIG welding, Friction stir welding, aluminum alloys, rotational speed.

### 1. Introduction

The coarse grain structure, micro crack and porosity were found in fusion welding like tungsten inert gas welding obtained due to persisting thermal conditions. when the fusion zone start to solidify. The formation of these defects on the weld region will result in reduction of weld strength about to half the parent material. To avoid these defects friction stir welding was introduced in 1991. The friction stir welding destroyed the coarse grain dendritic structure and generate new fine grain structure. Because of change in grains refinement and microstructure significantly improved the hardness of the friction stir processing (FSP) weld over the base metal.

The tool rotational speed, traverse speed, and tilt angle were basic parameters during the FSW process that have a substantial influence on the temperature distribution of the workpiece [1-2], the mechanical and metallurgical characterization of the welded joint [3] and material flow behavior [4]. The progress in numerical temperature simulations of FSW has been achieved by researchers and numerical analysis has found widespread application [5]. A moving source with a thermal distribution simulation the heat generated by friction between the rotating

tool and the work-piece was used in a heat transfer analysis [6]. In past studies, the heat flux was calculated based on the assumption that the sliding friction at the tool work-piece interface and the material flow was ignored [7-8].

Due to low heat generation in the friction stir welding, the residual stresses were also low in the weldment. The transverse force of friction stir welding tools plays an important role in stress measurement. The residual stresses in the weldment have a big impact on the performance of the welded structure. So far, information on the residual stress distribution of FSW has been limited. The effects of tool feed rate on residual stresses of FSW of Al-alloy joints were studied with synchrotron X-ray measurement and analyze the residual stresses in longitudinal and transverse directions [9].

The literature consists of the work conducted on various aluminum alloys by friction stir welding/processing. The study consist of various parameters, tool materials, tool dimensions, response parameters and results obtained by various researchers on magnesium alloys by friction stir processing. The literature in the tabular form is given below.

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Ref No	Author & year	Material Used	Processing Parameter	Conclusions
10	J-Q-Su et al [2002]	Aluminum alloy 7050-T65	The pin rotation speed was 350 rpm and the pin travel speed was 15 mm/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 recrystallized zone (DXZ).
11	S.Jana, et al [7]	Al-7Si-0.6 Mg alloy	The FSP tool had a pin height of 1.9 mm, a diameter of 4 mm at mid-pin height and a tool shoulder diameter of 12 mm. A process parameter combination of 2236 rpm and 2.33 mm/s was used for the FSP runs	FSP improved the fatigue life of a cast Al-7Si-0.6 Mg alloy by a factor of 15 when specimens were tested at the same stress level and at a stress ratio of R = 0.
12	Z.Y.Ma et al [2002]	7075Aluminum alloy	Two different processing parameters, i.e., 4 ipm/400 rpm and 6 ipm/350 rpm were used to generate the microstructures with different grain sizes.	Grain size will decrease in the temperature range of 420-530 and strain rate range of $1 \times 10^{-3}$ to $10^{-1}$ . For the $3.8 \mu\text{m}$ 7075Al alloy, super plastic elongation of 1250% were obtained at 480 in the strain rate range of $3 \times 10^{-3}$ to $3 \times 10^{-2}$ s <sup>-1</sup> , whereas the $7.5 \mu\text{m}$ 7075Al alloy exhibited a maximum ductility of 1042% at 5000 and $3 \times 10^{-3}$ s <sup>-1</sup>
13	R.S Mishra et al [2003]	Al-SiC Composite	Tool transfer rate of 25.4 mm/min and 101.6 mm/min is used for different target depth i.e. 1.78mm, 2.03mm, 2.28mm	When the target depth is too large (2.28mm), the shoulder of tool pushed away all the preplaced SiC particles and basically no surface composite formed. Too small target depth (1.78mm) was also ineffective to mix SiC particles into Al-alloy. A target depth of 2.03 mm resulted in incorporation of SiC particles in Aluminum matrix.
14	S. Jana et al [2007]	Cast Al-Alloy of F357	The tool rotation rate was 2236 rpm, and tool traverse speeds were 0.42, 0.98, 2.33 and 3.67 mm/s.	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
15	S. Jana et al [2010]	Al-7Si-0.6Mg alloy	Tool rotation rate of 2236 rpm and travel speed of 2.33 mm/s	FSP led to a five times improvement in fatigue life for a hypoeutectic Al-Si-Mg cast alloy. 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.
16	Z.Y.Ma et al [2005]	Al-4Mg-1Zr	The traverse speed of the tool 4ipm and the rotation rate of the tool 350 rpm was used	A maximum super plastic ductility of 1280 pct was observed at 525C and initial strain rate of $1 \times 10^{-1}$ s <sup>-1</sup> . The strain rate sensitivity of both as- extruded and FSP Al-4Mg-1Zr increased continuously with increasing strain rate from $1 \times 10^{-3}$ s <sup>-1</sup> to 1 s <sup>-1</sup> .

17	S.R.Sharma [2004]	A356 Alloy	One plate was processed using a standard FSW pin at 900 rpm and a traverse speed of 203.2 mm per minute and the other plate was processed using a triflute pin at 700 rpm and 203.2 mm per minute.	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 aluminum matrix as well as elimination of porosity.
18	Z.Y.Ma et al [2006]	Al-Si alloy A356	Five-pass FSP with a tool rotation rate of 700 rpm and a traverse speed of 203 mm/min was performed using a tri-flute pin.	Overlapping FSP did not affect the size, aspect ratio and distribution of the Si particles. The Si particles broken by FSP were uniform distributed in the entire processed zones created by multi pass FSP.
19	Z.Y.Ma et al [2004]	Al-Si alloy A356	Single pass FSP with a tool rotation rate of 700 rpm and transverse speed of 203 mm/min was performed on 6.35 mm	The flow stress of FSP A356 was significantly lower than that of cast A356 FSP. Maximum super plasticity of 650% was obtained at 530C and an initial strain rate of $1 \times 10^{-3} \text{ s}^{-1}$ in FSP A356.
20	Jianqing Su et al [2013]	Ti-6Al-4V alloy	Tool rotational speed (800-1000 rpm) and tool traverse speed (1-4 IPM) was used in this work.	The higher yield and ultimate tensile strength of 1067 MPa and 1156MPa without any losses of ductility were achieved in 900 rpm/4IPM sample having the smallest prior $\beta$ grains size of $\sim 12 \mu\text{m}$
21	Omar.S.Salih [2015]	Aluminium matrix composites (AMCs)	Tool rotation speed was 600, 800 and 1000 rpm and tool transverse speed was 40, 80 mm/min used	Welding parameters such as tool rotation, speed, transverse speed and axial force have a significant effect on the amount of heat generation and strength of FSW joints. Microstructural evaluation showed the formation of tunnel defect due to inappropriate flow of plasticized metal
22	N.Kamp et al [2006]	AA7449 aluminium alloy.	The interfacial energy of the different phases and the diffusion rates was taken	A numerical analytical model based on the Kampmann and Wagner numerical (KWN) model has been developed to predict the precipitate distribution evolution in 7xxx alloys during complex processing.
23	M. Maalekian et al [2008]	Steel Bar having Composition 0.75C, 1.02Mn, 0.28Si, 0.11Cr, 0.05Ni, 0.015S, 0.009P, 0.08Cu	function of process parameters $q = 2\pi.n.e.\mu.P$ Where q= heat flux, $\mu$ =Coulomb coefficient of friction, n= rotational speed, e = Amplitude, P= pressure	The heat-generation rate in orbital friction welding of steel bars is analyzed using four different methods; constant Coulomb friction, sliding-sticking friction, the experimentally measured power data and an inverse heat conduction approach.
24	L. Fratini et al [2010]	AA7075-T6	The tool rotation rate were 715 and 1500 rpm, and tool traverse speeds were 105 and 214 mm/min	The effects of in process cooling on the material characteristics and joint performance have been presented on AA7075-T6
25	S. Mironov et al [2011]	S31254 superaustenitic stainless steel	A tool rotational speed of 400 r.p.m. and a tool travel speed of 30 mm/min	The structural response of a typical low stacking fault energies (SFE) material S31254 to FSW has been studied. Formation of the final stir zone (SZ) microstructure was deduced to be primarily governed by discontinuous recrystallization occurring during the FSW cooling cycle.

26	Husain Mehdi et al., [2020]	AA6061 and AA7075	Tool rotational speed 1000-1300 rpm, feed rate 30-60 mm/min, tilt angle 0-2	The maximum tensile strength, percentage elongation, micro-hardness at nugget zone are 255 MPa, 29.2 and 105 HV at tool rotation 1300 rpm, traverse speed 45 mm/min and tilt angle 1°, whereas maximum residual stress (12.2 MPa) was found at tool rotation 1000 rpm, traverse speed 60 mm/min and tilt angle 0°. The application of FSP on TIG welded joint also improve the ductility of the welded joints, TIG+FSP welded joints are more ductile than the TIG welded joint due to fine grain structure.
27	Husain Mehdi et al., [2020]	AA6061 and AA7075	Tool rotational speed 800-1600 rpm, feed rate 63 mm/min	The asymmetry of the temperature distribution during TIG+FSP welding of AA7075 and AA6061 determined by numerical simulation corresponded with the experimental results. The peak temperatures on AS were higher than the RS of 20K. The heat transfer is analyzed by the effect of different processing parameters of FSP tool. The temperature at advancing side is higher than the retreating side. The predicted peak values of temperature at the weld region was calculated by the ANSYS software and found the maximum temperature about 515°C at tool rotation of 1600 rpm, whereas the maximum heat flux rate about $5.33 \times 10^6$ was observed at 1600 rpm
28	Y.S. Sato et al [2004]	Al Alloy 1100	Rotation speed of the welding tool was 500 rpm, and the traveling speed was 12 mm/sec	Friction stir welding (FSW) was applied to an accumulative roll-bonded (ARBed) Al alloy 1100. FSW resulted in reproduction of fine grains in the stir zone and small growth of the ultrafine grains of the ARBed material just outside the stir zone.
29	G. Buffa et al [2011]	A 3D FE model, with general validity for different joint configurations, was used to simulate	Tool rotating speed and tilt angle were kept constant and equal to 500 rpm and 21, respectively. Three levels of advancing velocity, i.e. 100, 225 and 325 mm/min were selected.	A new numerical procedure for the prediction of the residual stress distributions in Friction Stir Welding processes is Studied.
30	C. Hamilton et al [2008]	AA6061-T6 Aluminum alloy	Range of tool rotation rate 50 to 550 rpm was used.	A thermal model of friction stir welding was developed that utilizes a new slip factor based on the energy per unit length of weld. The thermal model successfully predicts the maximum welding temperature over a wide range of energy levels
31	Husain Mehdi et al., [2020]	AA6061 and AA7075	Tool rotational speed 1000-1300 rpm, feed rate 44 mm/min	The maximum compressive residual stress 64 MPa were located at the fusion zone (FZ) of the TIG weldment with filler ER4043, whereas minimum compressive residual stress 39 MPa was obtained at stir zone (SZ) of the TIG+FSP with filler 5356. The heat transfer is analyzed by the effect of different processing parameters of FSP tool. The temperature at advancing side is higher than the retreating side. The predicted peak values of temperature at the weld region was calculated by the ANSYS software and found the maximum temperature about 511°C at tool rotation of 1300 rpm.

32	Husain Mehdi et al., [2020]	AA6061 and AA7075 TiM	Tool rotational speed 1000-1300 rpm, feed rate 30-60 mm/min, tilt angle 0-2	The minimum compressive residual stress 18 MPa, maximum tensile strength (281.1 MPa), and hardness (107 HV) were located at the nugget zone of the TIG+FSP weldment at tool rotation 1300 rpm, traverse speed 30 mm/min with tilt angle 2. The large dimples and quasi cleavage with a sharp edge and various depth were found on the fractured tensile specimen surface of low tool rotational speed whereas fine dimples were found at high tool rotational speed. The average fine dimples (4.3 $\mu\text{m}$ ) were observed at high tool rotational speed.
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## 2. Conclusions

The present investigation have been carried out to assess the influences of friction stir processing on TIG welded joints to observed the optimum combination of parameters to attain better mechanical and metallurgical properties of pulse TIG and TIG+FSP welded joints of dissimilar aluminum alloys AA6061 and AA7075. From this study following conclusions can be obtained.

- The tensile strength of TIG welded joints with filler ER4043 and ER5356 was observed 158.6 MPa and 176.2 MPa respectively.
- The residual stress of TIG welded joints with filler ER4043 and ER5356 was observed 72 MPa and 63 MPa respectively
- To increases the tool rotational speed and decrease the feed rate, leads to increases in heat input in TIG+FSP welded joint.
- The maximum tensile strength (281.1 MPa), microhardness (107 HV) and minimum residual stress (18.3 MPa) for TIG+FSP welded joints with filler ER5356 was observed at tool rotational speed of 1300 rpm, traverse speed of 30 mm/min with tilt angle 2.
- The empirical relationships were developed to analyze the tensile strength, % elongation, residual stress and microhardness of TIG+FSP welded joint of AA6061 and AA7075 at 95% confidence level for both the filler ER4043 and ER5356.
- Optimized value of tensile stress, percentage elongation, microhardness at nugget zone and residual stress at nugget zone are 253.89 MPa, 31.05, 107.916 HV and 22.83 MPa respectively, whereas the optimized processing parameters i.e. tool rotational speed, feed rate and tilt angle are 1300 rpm, 45 mm/min and 0.955<sup>0</sup> respectively for filler ER4043.
- Optimized value of tensile stress, percentage elongation, microhardness at nugget zone and residual stress at nugget zone are 266.66 MPa, 29.74, 103.19 HV and 21.66 MPa respectively, whereas the optimized processing parameters i.e. tool rotational speed, feed rate and tilt angle are 1278.12 rpm, 35.98 mm/min and 1.749<sup>0</sup> respectively for filler ER5356.

- The grains in the nugget zone in TIG+FSP welded joint was observed much finer than the TIG welded joint at fusion zone.
- The peak temperatures on AS were higher than the RS of 20K. The heat transfer is analyzed by the effect of different processing parameters of the FSP tool. The temperature at the advancing side is higher than the retreating side.
- The predicted peak values of temperature at the weld region were calculated by the ANSYS software and found the maximum temperature about 515°C at tool rotation of 1300 rpm.
- The large dimples and quasi cleavage with a sharp edge and various depths were found on the fractured tensile specimen surface of low tool rotational speed whereas fine dimples were found at high tool rotational speed of TG+FSP welded joints.

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