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Research Article

Influence of Tool Geometry in Friction Stir Welding on Material Flow Pattern

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Abstract

Friction stir Welding (FSW) is a new solid state processing technique that can locally eliminate casting defects and refine microstructures, thereby improving strength and ductility, increasing resistance to corrosion and fatigue, enhancing formability. FSW can also produce fine grained microstructures through the thickness to impart super plasticity. Essentially, FSW is a local thermo mechanical metal working process that changes the local properties without influencing the properties of the bulk material. The aim of the present work is to study the influence of tool geometry on material flow during friction stir welding in Aluminum & Copper Alloys. Various types of tool geometries are modeled and the resulting flow patterns are analyzed. A FSW process with varying tool geometries and advancing speeds is numerically modeled, and a thermo-mechanically coupled, rigid-viscoplastic, fully 3D FEM analysis is done to predict the process variables as well as the material flow pattern and the grain size in the welded joints. Conclusions are drawn to identify the effect of operating process parameters.

Keywords: *FSW; FEM; Tool geometry; Material flow*

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1. Introduction

The environment friendly friction stir welding (FSW)) process is a potential and proven method for welding high-strength aluminium alloys. This solid-state localized thermo-mechanical joining process is predominantly used for butt and lap joints with no consumables. In general, the process is carried out by plunging a rotating FSW tool into the interface of two rigidly clamped sheets, until the shoulder touches the surface of the material being welded, and traversed along the weld line. The frictional heat and deformation heat are utilized for the bonding under the applied normal force. The primary heat source is frictional heat from tool shoulder and secondary heat source is deformation heat from the tool pin.The process and terminology of FSW are schematically explained in Fig. 1.

The advancing side (AS) is the side where the velocity vectors of tool rotation and traverse direction are similar and the side where the velocity vectors are opposite is referred as retreating side. The process parameters are

1. Tool Geometry,
2. Axial Force
3. Tool Rotation Speed,
4. Traverse Speed and
5. Tool Tilt Angle.

It is used already in routine, as well as critical applications, for the joining of structural components made of aluminum and its alloys. Indeed, it has been convincingly demonstrated that the process results in strong and ductile joints, sometimes in systems which have proved difficult using conventional welding techniques. The process is most suitable for components which are flat and long (plates and sheets) but can be adapted for pipes, hollow sections and positional welding. The welds are created by the combined action of frictional heating and mechanical deformation due to a rotating tool. The maximum temperature reached is of the order of 0.8 of the melting temperature.

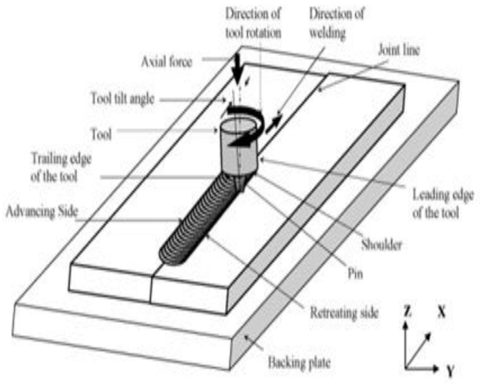

Fig : 1 Schematic layout of friction-stir welding process and terminology

The tool has a circular section except at the end where there is a threaded probe or more complicated flute; the junction between the cylindrical portion and the probe is known as the *shoulder*. The probe penetrates the work piece whereas the shoulder rubs with the top surface. The heat is generated primarily by friction between a rotating--translating tool, the shoulder of which rubs against the

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*Corresponding author: **T. Pavan Kumar** work piece. FSW involves complex interactions between a variety of simultaneous thermo mechanical processes. The interactions affect the heating and cooling rates, plastic deformation and flow, dynamic recrystallization phenomena and the mechanical integrity of the joint.

The microstructure of a friction-stir weld depends in detail on the tool design, the rotation and translation speeds, the applied pressure and the characteristics of the material being joined. There are a number of zones. The heat-affected zone (HAZ) is as in conventional welds. The central nugget region containing the onion-ring flow-pattern is the most severely deformed region, although it frequently seems to dynamically recrystallise, so that the detailed microstructure may consist of equiaxed grains. The layered (onion-ring) structure is a consequence of the way in which a tool deposits material from the front to the back of the weld. The thermo mechanically-affected zone lies between the HAZ and nugget; the grains of the original microstructure are retained in this region, but in a deformed state. The top surface of the weld has a different microstructure, a consequence of the shearing induced by the rotating tool-shoulder.

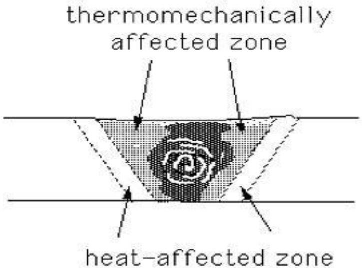


Fig : 2 Heat Effecting Zone

The half–plate where the direction of rotation is the same as that of welding is called the advancing side, with the other side designated as being the retreating side. This difference can lead to asymmetry in heat transfer material flow and the properties of the two sides of the weld.

Since its discovery in 1991, FSW has evolved as a technique of choice in the routine joining of aluminum components; its applications for joining difficult metals and metals other than aluminum are growing, albeit at a slower pace. There have been widespread benefits resulting from the application of FSW in for example, aerospace, shipbuilding, automotive and railway industries.

1.1. Heat Generation

During FSW, heat is generated by friction between the tool and the work piece and via plastic deformation. A fraction of the plastic deformation energy is stored within the thermo mechanically processed region in the form of increased defect densities. In the weld, a mixture of recovery and recrystallization phenomena occur simultaneously. Deformation not only increases the dislocation density but also the amount of grain surface and grain edge per unit volume and by cutting precipitates may force them to dissolve.

In FSW, the tool moves along the weld joint at a constant speed U, as it rotates about its axis with speed ω. At any point on the tool work piece interface, the tangential speed of the tool with respect to the work piece is given by

$v_r = \omega r - U \sin\theta$

Where r is the radial distance from the tool-axis and θ is the angle between radial vector, r, and the welding direction. The term U sin θ may be neglected when ωr is much larger. Heat is generated due to friction and plastic deformation at the tool-work piece interface and due to plastic deformation in the TMAZ. The local interfacial heat generation due to friction is the product of frictional force and the sliding velocity. The interfacial deformation heat is the product of shear stress and the velocity of the work piece material which sticks to the tool as it moves.

Shear deformation

1.2. Heat Transfer and Material Flow

Except for the initial and the final periods of welding, i.e., during tool–pin insertion and extraction, the heat generation occurs at a constant rate if the tool rotates and moves forward at a constant speed. This steady–state assumption is justified by the fact that the weld profile and properties remain roughly constant during the welding phase.

Of the heat generated at the shoulder/work–piece interface, some of it is transported into the tool material while the rest enters the work–piece.

Most of the material flow occurs through the retreating side and the transport of the plasticized material behind the tool forms the welded joint. Three types of flow affects the overall transport of plasticized materials during FSW.

1. First, near the tool, a slug of plasticized material rotates around the tool. This motion is driven by the rotation of the tool and the resulting friction between the tool and the work piece.
2. Second, rotational motion of the threaded pin tends to push material downward close to the pin which drives an upward motion of an equivalent amount of material somewhat farther away.
3. Finally, there is a relative motion between the tool and the work piece.

The overall motion of the plasticized material and the formation of the joint results from the simultaneous interaction of these three effects.

The flow during FSW differs in character from material flow in the liquid state during conventional fusion welding. This is evident from welding of dissimilar metals. During fusion welding, the weld pool becomes compositionally homogenous after solidification. However, during FSW of dissimilar metals, mixing does not occur in atomic scale, and it is possible to find larger concentration differences in the weld metal and the region is far from homogenous.

During FSW, the material near the top of the work–piece is stirred under the action of the shoulder and vertical component of motion occurs mainly due to tool-pin. The stirred material from the top is carried down and deposited in the weld nugget. The vertical mixing becomes prominent at low weld pitch, which is the ratio of welding speed to rotational speed.

The welding variables and the material properties affect the temperature profiles, cooling rates, microstructure and the resulting properties of the welded joint. The temperature fields in FSW exhibit certain special features. The peak temperatures are significantly lower than those attained in conventional fusion welding processes.

1.3. Welding Variables

The welding speed, the tool rotational speed, the vertical pressure on the tool, the tilt angle of the tool and the tool design are the main independent variables that are used to control the FSW process. The heat generation rate, temperature field, cooling rate, x-direction force, torque, and the power depend on these variables.

During FSW, the torque depends on several variables such as the applied vertical pressure, tool design, the tilt angle, local shear stress at the tool material interface, the friction coefficient and the extent of slip between the tool and the material. Measured torque values can provide some idea about the average flow stress near the tool and the extent of slip between the tool and the work piece for certain conditions of welding, when other variables are kept constant. The torque decreases with increase in the tool rotation speed due to increase in the heat generation rate and temperature when other variables are kept constant. It becomes easier for the material to flow at high temperatures and strain rates.

1.4. Tool Design

The presence of residual stress in a weld plate affects its distortion behaviour and ability to sustain applied loads while maintaining structural integrity. As in ordinary welds, residual stresses develop in constrained assemblies during FSW due to expansion during heating and contraction during cooling; a feature unique to FSW is the additional stress caused by the rotational and translational components of the tool. The stirring action of the tool is believed to relieve some of the stresses within the thermo mechanically affected zone.

Tool geometry is considered to be one of the prime parameters which controls the material flow and heat input, and in turn the quality of the weld. Most of the tool design is based on intuitive concepts. The first step in deriving the concept of FSW tool design is to understand the role of tool in friction stir weld formation.In solid-state welding, the accepted principle of weld formation is stated that the bonding occurs, when a pair of contamination-free surfaces are brought together in the range of inter-atomic-distances and the force utilized for bonding is the inter-atomic force. In most of the solid-state welding process, like forge welding, diffusion welding, friction welding, explosive welding, ultrasonic welding, roll bonding, etc., the bonding is established by generating fresh metal-to-metal contact by eliminating oxide layers and impurities from the interface under required pressure and temperature. These process conditions modify the base material interface to satisfy the solid-state welding condition, and do not generate any additional surfaces in the material. In contrast, due to the third body (the FSW tool) interaction in FSW, additional interfaces are generated during the process. Finally, all the surfaces are coalesced with each other by the applied pressure and temperature, and thus, the sound solid-state weld is produced. Therefore, the mechanism of weld formation in FSW will be clearly known only when the role of tool is understood. The material flow analysis is an important tool to understand the role of FSW tool on the of weld formation. Tool design influences heat generation, plastic flow, the power required, and the uniformity of the welded joint. The shoulder generates most of the heat and prevents the plasticized material shoulder and the tool–pin affect the material flow. In recent years several new features have been introduced in the design of tools.

Design of tools should be based on a quantitative understanding of material flow. Tool wear is an important concern for the FSW process, particularly for high temperature harder alloys. There is a need for the development of reliable models for the wear of the FSW tools.

The material flow in the pin driven region is only influenced by the pin it is important that the pin should be designed such that maximum amount of transferred material is retained in the weld cavity. Similarly shoulder should be designed such that maximum amount of ejected material from the weld cavity by the pin is reflected back into the weld cavity.

1.5 Material Flow

In FSW research, the study of metal flow around the tool during welding is very important to improve process productivity and weld properties. Flow visualization studies have already been conducted by several authors using different techniques: introducing marker materials into the weld line, using etching contrast to enhance the flow patterns in the weld, welding dissimilar materials and performing numerical simulation studies. despite the limitations associated with all the techniques used, which are well documented in the literature, the main metal flow mechanisms have already been established, being found that vertical, straight through and rotational flows of plasticized material take place in the vicinity and around the tool, dragging the bulk of the stirred material to a final position behind its original position. In the wake of the weld, behind the travelling tool, material deposition takes place layer by layer, resulting in the formation of the banded structure of the nugget. Variations in tool geometry and/or plate thickness do not change the main flow mechanisms, but greatly influence the amount of material dragged by the shoulder or by the pin, from the retreating and advancing sides of the tool, as well as the periodicity of the deposition at the trailing side of the tool, which, in turn, influences the final morphology of the weld.

Material flow phenomenon in Fsw takes place in two modes. The first mode takes place layer by layer and is caused by tool shoulder while the second mode is caused by the extrusion of the plasticized metal around the pin.

Table.1 Composition of Aluminum Alloy AA6061

Element	**Al**	**Mg**	**Si**	**Cu**	**Cr**
Amount (wt %)	97.9	1.0	0.6	0.8	0.2

Table. 2 Composition of Cu Alloy AA7075

Element	**Al**	**Cu**	**Mg**	**Cr**	**Zn**
Amount (wt %)	90.0	1.6	2.5	0.23	5.6

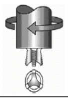
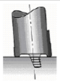
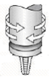
Tool	Cylindrical	Whorl™	MX triflute™	Flared triflute™	A-skew™	Re-stir™
Schematics						
Tool pin shape	Cylindrical with threads	Tapered with threads	Threaded, tapered with three flutes	Tri-flute with flute ends flared out	Inclined cylindrical with threads	Tapered with threads
Ratio of pin volume to cylindrical pin volume	1	0.4	0.3	0.3	1	0.4
Swept volume to pin volume ratio	1.1	1.8	2.6	2.6	depends on pin angle	1.8
Rotary reversal	No	No	No	No	No	Yes
Application	Butt welding; fails in lap welding	Butt welding with lower welding torque	Butt welding with further lower welding torque	Lap welding with lower thinning of upper plate	Lap welding with lower thinning of upper plate	When minimum asymmetry in weld property is desired

Fig: 3 Tool Geometry for Friction Stir Welding

Defects

Common defects in friction stir welds include porosity and surface defects. At a constant rotational speed, an increase in the travel speed leads to wormhole initiation near the bottom of the weld. Furthermore, the size of the wormholes increases with the travel speed because of inadequate material flow towards the bottom of the weld. Most of the heat generation occurs at the interface between the tool shoulder and the work–piece. Significant heterogeneity in heat generation at that interface can lead to defect formation in the form of excess flash due to surface overheating. Tool design and welding variables affect materials flow patterns.

2. Present work

The study envisages studying the influence of tool design on material flow. Material flow controls the quality of joint which in turn influences the mechanical properties as well as the weld integrity. In friction stir welding material flow occurs in plastic condition. Improper flow would result in the formation of defects, thus, it is of paramount importance to stream line the flow the material. Flow of the material is dictated by tool geometry coupled with weld pool temperature.

Experiments are conducted by varying pin geometries (cylindrical, conical & knurling) and advancing speeds and also numerically modeled and analyzed using FEM analysis to predict the material flow pattern and the grain size in the welded joints.

Aluminum alloys are important for the fabrication of components and structures which require high strength, low weight or electric current carrying capabilities to meet their service requirements. Among all aluminum alloys, AA 6061 alloy plays major role in the aerospace industry in which magnesium and silicon are the principal alloying elements. It is widely used in the aerospace applications because it has good formability, weldability, machinabilty, corrosion resistance and good strength compared to other aluminum alloys. When using the conventional arc welding techniques, long butt or lap joints between AA 6061 and other aluminum alloys are particularly difficult to make without distortion because of high thermal conductivity and special welding procedures and high levels of welder skill are generally required

3. Experimental Work

In this investigation, aluminum alloy sheets with thicknesses of 3 mm were used. The sheet was cut to required size by power hacksaw cutting and followed by grinding to remove the burr. The main alloying elements in this alloy are 4.2 wt% Mg and 0.42 wt% Si. Butt joint configuration was used to fabricate the friction stir welds. A fixture is designed to hold the plate in rigid position. The joint was initially obtained by securing the plates in position using mechanical clamps. A non-consumable tool made of HCHC steel was used to fabricate the joints. The welding tool was composed with a shoulder which is made of HCRC steel with 14.5mm diameter and pin diameter is 6mm and 2.6mm in length. The experiments performed with five different types of tools cylindrical, conical, screw threaded, groove, & knurling. A series of welds are carried out using BFW make knee type mill Milling machine. Aluminum sheets of 3mm thickness are welded together at various speeds of 700rpm, 1000rpm, 1400rpm & 2000rpm with different tool geometries mentioned above and also with cu sheets of 3mm thickness. The welding speed is 10mm/min, 20mm/min/35mm/min & 50mm/min for 700rpm, 1000rpm, 1400rpm &2000 rpm respectively shown in Table 3. Metallographic sectioning at various orientations and etching with kellar's reagent the micro structure observation is done which is used to notice material flows. As copper is not etched with kellar's reagent material flow can more easily observed in Al-Cu welds.

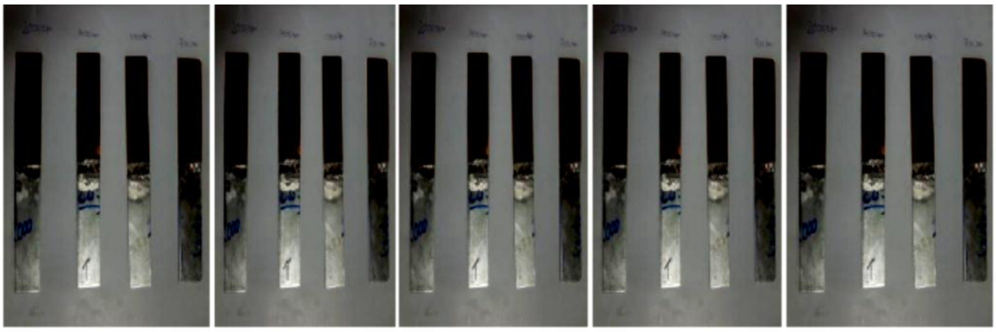
Fig: 4 FSW tool-HCHC

Table 3: Welding Factors and their levels

Process parameters	Unit	Samples set 1	Samples set 2	Samples set 3	Samples set 4
Rotation speed	rpm	700	1000	1400	2000
Transverse speed	mm/min	10	15	35	50
Offset	mm	3	3	3	3
Plunge depth	mm	2.6	2.6	2.6	2.6
Axial force	KN	7	7	7	7

(a) (b) (c) (d) (e)

Fig : 5 Tensile test specimens of Fsw welds (Di similar Al Alloys)at diiferenr rpms using (a) Cylindrical Tool (b) Conical Tool (c) Knurling Tool (d) Groove Tool (e) Cylindrical Thread Tool



(a) **(b)** **(c)** **(d)** **(e)**

Fig : 6 Tensile test specimens of Fsw welds (Di similar Cu & Al Alloys)at diiferenr rpms using (a) Cylindrical Tool (b) Conical Tool (c) Knurling Tool (d) Groove Tool (e) Cylindrical Thread Tool

5. Resuls and Discussions

Following were observed when welding is performed with Al on advancing side of the tool resulted in flash formation.

1. When the copper is located at the retreating side of the tool it Will be transported by the shoulder to the advancing side where aluminum alloy is located this is because during welding the retreating side material is dragged to the advancing side by the shoulder at the trailing side of the tool.

2. When aluminum is located at the retreating side of the tool it will be dragged by the shoulder to the advancing side of the copper which is more harder is located due to which inter mechanical structures are resulted.

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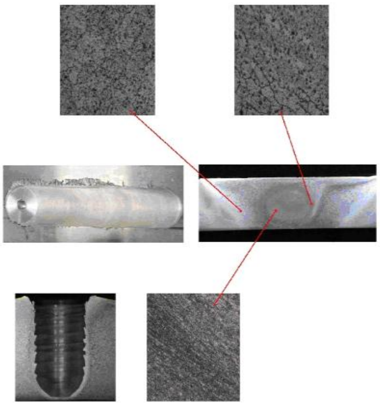

Fig: 7 Microstructure of welments using threaded tool

The fig no. 5 and 6 show the speicimens of the weldments welded with different tool geometry at different rpms for disimilar aluminiuma and copper alloys used for testing

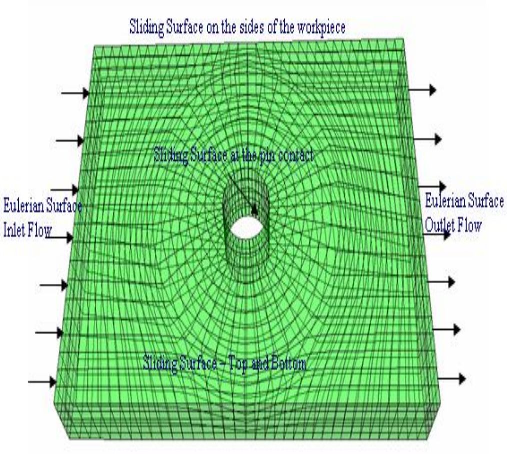

Fig : 8 Meshing Of Fem Model

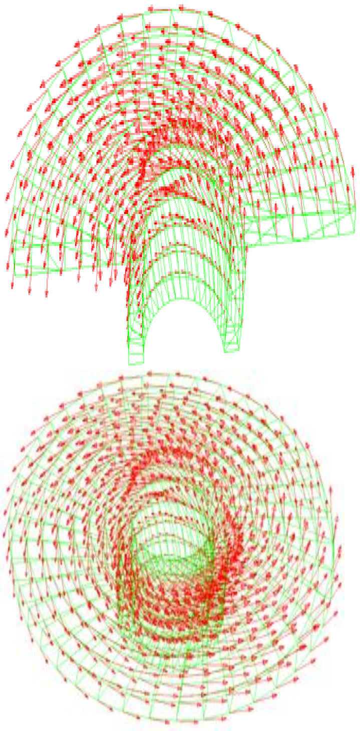

Fig: 10 Material Flow Pattern developed using FEM under tool shoulder and around the pin at 1400rpm, 35 mm/min for threaded tool

Conclusions

Material flow by friction stir welding was investigated with experimental data and numerical studies which gave the following results

1. Material flow pattern on the retreating side is in the rotating direction of the screwed tool.
2. Material flow pattern at the advancing side is in the reverse direction of tool rotation.
3. Material flow pattern from Advancing side to retreating side is observed to be passing behind the pin.
4. Material flow velocities at Advancing Side are faster than Retreating side.

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