Friction Stir Welding: A Review

Ganesh Y. Surve[1], Vijay S. Jadhav[2]

[1]PG Scholar, Government College of Engineering, Karad (M.S.) India

[2]Associate Professor, Government College of Engineering, Karad (M.S.) India

Abstract – This paper gives a brief overview about the friction stir welding (FSW) as an advanced welding process. FSW is a solid state welding process has different advantages over conventional welding such as no fumes, spattering and distortion which gives strong weld strength. In FSW pieces are clamped together by suitable clamping system or fixtures. It uses a non-consumable tool which is plunged in a workpiece causes a frictional heat which produces a welded joint. Generally heat produced in a weld is 2/3rd of melting point of base metal. Weld is produced without significant melting hence free of solidification defects, cracking and low distortion problem. Also there is no need to use protective gases like conventional welding. Tool material selection and design predominantly affects performance of a tool. Tool geometry also affects the material flow hence there is need to improve properties of weld by selecting proper tool geometry of a tool. Due to the temperature distribution base material undergoes different microstructural behaviour as unaffected parent zone, heat affected zone, thermo-mechanically affected zone and weld nugget zone. Different weld zones show different mechanical properties.

Keywords— Plunge Depth, Advancing Side, Dwell, Heat Affected Zone, Heat Generation, Plunge Depth.

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1. INTRODUCTION

Friction stir welding is invented at The Welding Institute (TWI) UK in 1991[1]. In contrast with conventional welding two objects are placed with no gap and high pressure. Third body is rubbed against two clamped objects. This tool is plunged into the joining region of two objects and translated along joint line [2]. Tool rotational speed, plunge depth and tool geometry mostly influences the quality of weld joint which can withstand the deformation without premature failure during post weld forming [3].

FSW tool is a critical component in the success of a weld. Tool consists of rotating round shoulder and threaded pin that creates friction followed by heating by softening alloy [5]. However FSW tool experiences high stresses and high temperature for a particular hard alloys such as steels and titanium alloys [4, 5, 6].

The necessary power requirement is a function of various parameters that includes material, feed rate, spindle speed, tool geometry and tool depth. FSW is immune to the defects and property deteriorations such as melting, elimination of fumes, porosity, spatter, low shrinkage and weld distortion. In addition to the extensive mechanical deformation induces dynamic recovery and dynamic recrystallization that refine microstructure [7]. Tool material is sufficient harder than base metal so that it creates a sufficient friction, heat and sound weld. As steel is harder than the aluminium it requires the more frictional heat. The dependence on friction and plastic work precludes significant melting in workpiece and avoids many difficulties arising from change of state.

2. FRICTION STIR WELDING PRINCIPLE

It uses a non-consumable tool consisting of shoulder and pin which rides on the surface and plunge into the workpiece respectively. The plates are typically placed with no gap between them. Tool is forced in order to achieve a sufficient plunge depth to achieve a heat generation.

The tool is plunged up to the back of a shoulder and then it is dwell for few seconds. At first material is removed in the form of chip as both tool and workpiece are at room temperature. At the temperature is increased due to the friction, material goes in plastic stage. After sufficient temperature is reached, tool is traversed along weld line. After completing a weld a tool is retracted from weld, leaving a key hole in the workpiece. As the tool is arrived at the end it is not possible to travel forward leaving a key hole. As this key hole is not useable it is required to be trimmed.

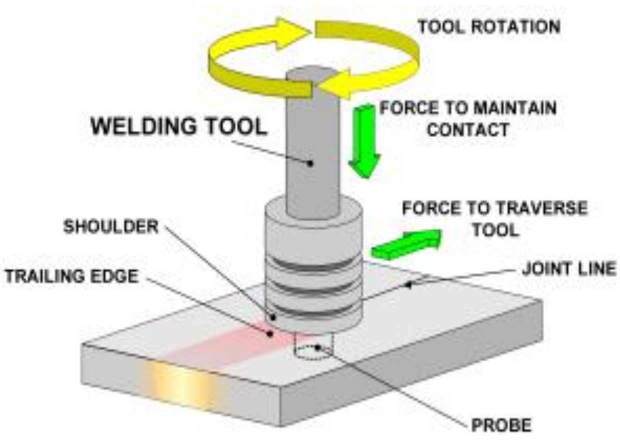

Fig. 1 Friction Stir Welding Process

It uses a non-consumable tool consist of [21]

A. Shank

It is the end tail part of a tool. Shank is generally used for holding the tool in to the spindle of a machine.

B. Shoulder

Shoulder is responsible for the generation of heat. Large amount of heat is generated due to larger surface area. Recent advances are developed in the shoulder surfaces.

C. Pin

It is the lower area of tool. The height is slightly lower than the thickness of workpiece. Its main function is to mix the material between advancing side and traversing side.

3. VARIABLES AFFECTING FRICTION STIR WELDING

It is a solid state joining process in which it is heated with significant melting. As a result FSW process consists of number of variables. For the suitability of the process with specific application it is necessary to know hardness, tensile strength and fatigue behaviour of a base material. Process parameters have a high impact on the welding efficiency. Therefore it is necessary to know the response of variables on the mechanical properties of a FSW process.

Table 1 Variables affecting the process parameters

Process Parameter	Variables
Tool Design	Height of plunge Tilt Angle Plunge depth Tool Material Shoulder diameter
	Tool Geometry
Design of Fixture	Clamp Forces Alignment
Material	Thickness Melting Point Mechanical properties Coefficient of thermal expansion
Machine	Axial force Rotational speed Transverse Speed Position control
Process Parameter	Variables

4. STEPS IN FRICTION STIR WELDING

A. Plunging

It consists of plunging of a non-consumable tool in to the base metal. At first both tool and base metal are at room temperature therefore as the tool plunges in to the base metal is removed are in the form of chips.

B. Dwell

It is the time in which tool is rotated stationary at the surface of workpiece. As the time advances a sufficient heat is developed at the interface of tool and workpiece. Metal goes in to the plastic state due to the friction developed between shoulder of tool and workpiece.

C. Transversing

After the sufficient heat is generated tool is transverses along the weld line of a joint. As the tool is transverses a defect free weld is formed due to heat is generated by friction and rubbing action of a tool.

D. Retracting

It is the last step in which tool is retracted from the weld. After the necessary tool transverse along the weld line tool is retracted from the workpiece remaining the tool pin mark on the workpiece.

5. TERMINOLOGIES USED IN FRICTION STIR WELDING

A. Advancing Side (AS)

At one side where tool rotation direction remains same as the welding direction is called as the advancing side. [9]

B. Retracting Side (RS)

It is the side where tool rotation direction is opposite as the welding direction. A more amount of heat is generated than advancing side due to the more friction. [9]

C. Plunge Depth

It is the depth in which shoulder is plunged in to the surface of a weld. As more plunge depth is applied resulting into the more heat and lower the thickness of a weld. And lower the plunge depth lower is the heat generated.

6. MICROSTRUCTURE OF FRICTION STIR WELDING

Generally in a Friction stir welding process, due to the friction, material is heated to the plastic state therefore different microstructural behaviour is observed. The joint consist of four different microstructural zones as follows [16]:

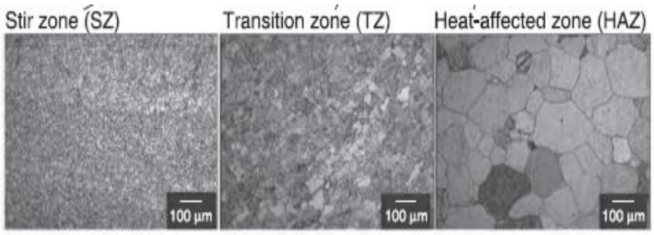

Fig. 2 Microstructure of the SZ or NZ, TZ and HAZ of the FSPed AZ31B Mg alloy [17]

A. Unaffected Parent Material

This is the material which is not undergone the thermal heat due to the friction between rotating tool and stationary base material. Mechanical properties and microstructural behaviour of a base material and unaffected parent material are same. This is the zone other than HAZ, TMAZ and SZ.

B. Heat Affected Zone

This is the zone in which microstructure and mechanical properties are affected by heat generated due to welding process while there is no actual mechanical deformation of a material is observed in this zone.

C. Thermo-Mechanically Affected Zone

This is the zone in which tool actually plastically deforms the material and generated heat has some effect on the on the material. The common features of this zone are the elongated structure and rotated grains due to rotatory action of a tool. The generation of heat is different in both the sides of the tool travel. In A.S. where tool rotational direction is same as the tool translation creates lower amount of heat than the R.S. While R.S. where tool rotational direction is different than the tool translational direction.

D. Weld Nugget Zone

This is the zone in which actually tool is translated through the joint. Here pin of a tool mixes the material from both sides. It is the centre area of a weld where most heat is generated. The amount of heat generated is depends upon the welding parameters such as welding speed, tool rotational speed, axial force, tilt angle, plunge depth and many other parameters. The grains are observed in this zone is smaller than the base zone. While concentric rings are observed on to the weld nugget zone is influenced by a pin and shoulder geometries. [18,19]

7. HEAT TRANSFER AND MATERIAL FLOW

Friction stir welding provides sound, defect free weld joint. Generally heat transfer and material flow in welding depends on number of variables including design of tool, thermal conductivity, properties of a tool as well as weld material.

About 80% to 90% of the melting temperature of base material is observed at tool-workpiece interface. About 20% of total heat is attributed to the pin [22, 23]. Generally heat is generated due to friction and plastic deformation which takes place between tool and workpiece interface [24, 25]. Tool workpiece interface takes place between shoulder-workpiece and pin-workpiece interface. Large amount of heat is generated between shoulder-workpiece interface rather than pin-workpiece interface. Heat is generated at shoulder-workpiece interface due to frictional heat is larger than plastic deformation.

Heat transfer takes place in three phases

A. Dwelling

It is heat transfer in which material is heated by stationary rotating tool in order to achieve a sufficient increase in temperature for the transverse movement of a tool. Increase in temperature of a tool workpiece interface precludes a sound weld joint.

B. Transient Heating

A small decrease in temperature is observed during this stage. It is the stage in which tool begins transversal moment until pseudo steady state is reached.

C. Effective constant thermal field.

Finally pseudo steady state is where the system reaches an effective constant thermal field around the tool.

The relative velocity at same point on both side of AS and RS is not the same due to combination of rotation direction and transverse direction of tool. This leads to asymmetrical heat transfer and material flow. [16]. FSW involves complex interaction between heat generation, plastic deformation and metallurgical aspects.

8. PRINCIPLES OF HEAT TRANSFER AND MATERIAL FLOW

Nature of heat transfer and material flow is primarily affected by the tool geometry, applied torque, rotational speed of tool and thermo-mechanical conditions experienced by a tool as well as the base materials. Shoulder size, surface angle, pin geometry, inclinational angle influences the heat transfer mechanism and material flow behaviour.

In friction stir welding shoulder surfaces used are generally flat, convex and concave shaped. While pin geometries used are cylindrical, tapered, triangular, square, hexagonal and inverse tapered [2]. Tools with non-circular geometry experienced pulsating effect due to eccentricity. Tool profile with non-circular geometry provides better plastic material flow. Shoulder surface angle affects axial force and consequently pressure distribution [15]. Large amount of material is flowed due to shoulder surface area while layer by layer material is flowed due to pin [2].

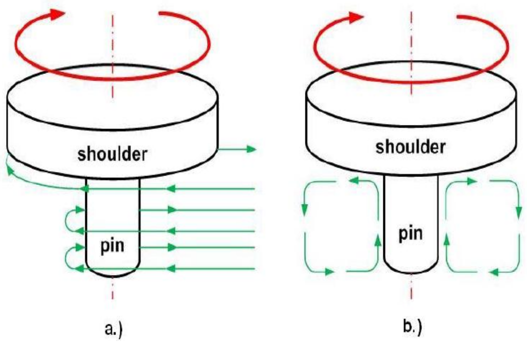

Fig. 3 Material Flow Behaviour

a. Horizontal material flow behaviour

b. Vertical material flow behaviour

9. FRICTION STIR WELDING TOOLS

A non-consuming, rotating tool is used for metallurgical defect free welds. There are three main functions of friction stir welding are as follows.

A. Tool is generally used for the heating the workpiece.

B. Controlling and moving the plasticized material.

C. Controlling the plasticized material under the tool shoulder along the weld line.

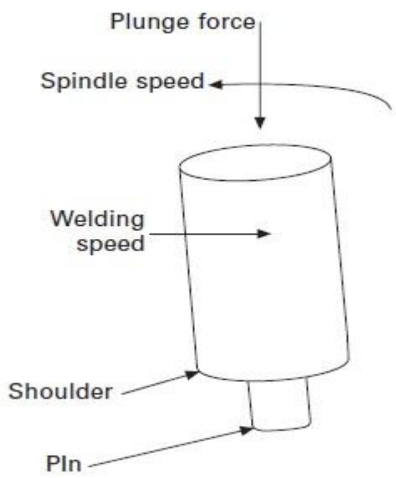

Fig. 4 Friction stir welding tool

Generally friction stir welding tools are designed in order to improve the welding joint efficiency by,

A. Maximum possible welding speed in order to increase the productivity.

B. Improving mechanical performance of a tool.

It uses a non-consumable tool consist of

Shank, shoulder and pin are the three components of a welding tool. Large amount of heat is generated at the shoulder and workpiece interface. By applying sufficient plunge depth constraints the plasticized the material around the pin and prevents the escaping of a material [20]. Negligible amount of heat is generated by pin meanwhile its main function is to maximize the mixing of a material from advancing side to retracting side.

10. FRICTION STIR WELDING TOOL MATERIALS

For the production of a sound weld a proper tool design along with proper tool material is required. Material is sufficient hard enough than base metal in order to generate a heating effect.

Therefore tool should have following properties

A. Good mechanical strength

B. Good wear resistance

C. Good fracture toughness

D. Low coefficient of thermal expansion

E. Good machinability

Tool steel is the most widely used tool material for aluminium and its alloys [26]. Other tool steels used include oil and water hardened, D2, diver. Oil & water hardened tool steel has application up to the 500º c while secondary hardened tool steel has application up to 600ºc.

Table 2 Tool Materials and Their Working Temperature and Weldable Materials

TOOL MATERIALS	WORKING TEMPERATURE	WELDABLE MATERIAL
H13 Tool Steel	500˚-600˚C	Aluminium, copper and Magnesium Alloys
HCHCr	------	Magnesium alloys
Tungsten Carbide	1000˚C	Aluminium metal matrix composites
Nickel alloys	600˚-800˚C	Copper alloys
PCBN	2600˚-3000˚C	Copper alloys, stainless steels & nickel alloys, titanium alloys.
Oil hardened non shrinking	------	Aluminium and magnesium metal matrix

CONCLUSION

This paper describes the principle and summery of friction stir welding. FSW is the best process for different alloys of aluminium with excellent weld quality. Heat generation is the main reason for welding and it can be achieved by proper tool design with optimized pin profile geometry. However more heat generation is required for the alloys such as steel, titanium and magnesium alloys hence there is a growing demand in a development of tool. Tool design influences the material flow, temperature distribution and mechanical properties of weld. The material flow in a FSW is still not fully understood due to complexities and relations with tool design.

This process is also used for dissimilar welding has various applications in defence industries. FSW process replaces the costlier riveting process in an aerospace industry that gives sufficient strength of a weld.

ACKNOWLEDGMENT

Author wishes to thanks Mr. S. S. Sandbhor (Senior Design Manager) for their valuable guidance. Also thanks to Dr. S. S. Mohite, H.O.D. of Mechanical Engineering, GCE, Karad, for their continuous support and suggestions during this project work.

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Corresponding Author

Ganesh Y. Surve*

PG Scholar, Government College of Engineering, Karad (M.S.) India

E-Mail – surve.ganesh99@gmail.com