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Friction Stir Welding: An Overview

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Abstract:- **Friction Stir Welding (FSW) is a new, environmental friendly and energy saving solid phase joining technology that has gained keen focus of research in the welding field. This article provides a comprehensive insight on basic principle of FSW, the process parameters of FSW, and tool design. It also covers weldability, property enhancement, and a review of potential advantages and applications of the process. Joining of alloys could be a major problem in many sectors that include automotive, aerospace, ship building industries, and so on; where fusion welding is not possible due to large difference in physical and chemical properties of the components to be joined. FSW can solve such problems as it can join different alloys of aluminium and also of hard materials like steels because it avoids the common problems obtained in conventional welding processes. Common welding defects arise during welding of dissimilar materials such as porosity, solidification cracking and chemical reactions. It can be avoided with optimized FSW provided special attention is paid to the process parameters, tool design and joint design.**

Keywords:-- **Friction Stir Welding, Weldability, Process parameters**

I. INTRODUCTION

Friction stir welding (FSW) was invented by Wayne Thomas at The Welding Institute (TWI) at Cambridge in United Kingdom in the year 1991. It was initially applied to aluminium alloys. FSW is a solid state material joining process which produces welds of high quality, high strength with low distortion in difficult to weld materials. FSW is the joining process accomplished by material flow below the melting temperature. Hence the defects caused by joint melting such as porosity, and alloys segregation can be eliminated or adequately reduced. These process specialities have made FSW very practical for joining dissimilar alloys [1].

FSW is considered to be the most significant development in metal joining in a decade and is a "green technology" due to its energy efficiency, environment friendliness, and versatility [2].

The key benefits of FSW are [3]:

- As a solid state process it can be applied to various alloys and avoids problems of hot cracking, porosity, element loss, grain boundary cracks, etc., common to fusion welding processes.
- As a mechanised process FSW does not rely on specialised welding skills, indeed manual intervention is seldom required.
- No shielding gas or filler wire is required.
- The process is remarkably tolerant to poor quality edge preparation.
- The absence of fusion removes much of the thermal contraction associated with solidification and cooling, leading to significant reductions in distortion.
- It is very flexible, being applied to joining in one, two and three dimensions, being applicable to butt, lap and spot weld geometries; welding can be conducted in any position.
- Excellent mechanical properties, competing strongly with welds made by other processes.
- High welding speeds and joint completion rates in a single pass. Thick plates can also be joined by FSW on either side.

II. PROCESS OVERVIEW

The basic principle behind FSW comprises of a non-consumable rotating tool with specially designed pin and shoulder, inserted into the abutting edges of two plates to be joined and subsequently traversed along the joint line definitions as shown in fig 1.

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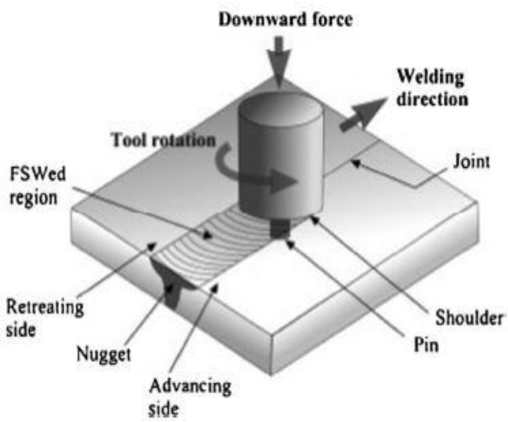

Fig 1: Friction Stir Welding Process

The FSW process includes three phenomena namely, heating, plastic deformation and forging. Heat is generated through both friction and plastic deformation of the welded material. At elevated temperatures, the material plasticizes and is sheared at the front of the probe and it is rotated to the rear of the probe where it is forged together under significant shoulder pressure. The advancing side is the region in which the traverse velocity and the tangential velocity of the rotating tool are in the same direction. The retreating side is the region in which the traverse velocity and the tangential velocity of the rotating tool are in the opposite directions. This advancing retreating phenomenon leads to different mixing characteristics within the weld seam [4]. FSW can be used to produce butt, corner, lap, T, spot, fillet and hem joints, as well as to weld hollow objects, such as tanks and tubes/pipes, stock with different thicknesses, tapered sections and parts with 3-dimensional contours [5].

III. WELDABILITY

Weldability is also known as join-ability, and refers to the ability of a material to be welded under the fabrication conditions imposed satisfactorily on the intended surface. A material's weldability is used to determine the welding process and to compare the final weld quality to other materials. In the process of FSW, the material selection is an important part. This is because, based on the substrate material the other parameters like tool material, welding speed, rotational speed, and down force are decided. FSW was originally invented for welding aluminium alloys, as some grades of aluminium are considered difficult to weld such as a very high strength 2xxx and 7xxx series of alloys. With FSW process, rapid and high quality welding of such alloys, traditionally considered unweldable has become possible. It is also possible to weld different combinations of metals, whose plasticizing temperatures are quite similar. The technique continues to be advanced and refined for the joining of a various materials such as,

1. Magnesium and Magnesium alloys
2. Copper and Copper alloys
3. Titanium and Titanium alloys
4. Hafnium and Zirconium
5. Inconel and Super alloys
6. Steel and Ferrous alloys
7. Nickel alloys
8. Zinc
9. Lead
10. Thermoplastics

IV. FRICTION STIR TOOL

FSW is a thermo-mechanical deformation process where the tool temperature approaches the solidus temperature of the base material. The friction stirring tool consists of a pin or probe, and a shoulder. Contact of pin with the work-piece creates frictional and deformational heating and softens the work-piece material; contacting the shoulder to the work-piece increases the work-piece heating, expands the zone of softened material, and constrains the deformed material [6].

A. Tool material characteristics

Production of high quality friction stir welds requires proper tool material selection for the desired application. Significant material characteristics to be considered while selecting the material for FSW are:

1. Resistance to wear.
2. Low coefficient of thermal expansion.

B. Ambient and elevated temperature strength.

3. Elevated temperature stability.
4. Tool reactivity.
5. Good fracture toughness.
6. Good strength and dimensional stability.
7. Good oxidation resistance.
8. Machinability.

C. Tool material

In the FSW of aluminium alloys, the wear of the tool is not as much. As such, tool materials such as tool steels can be used. However, in the FSW of high melting point materials such as steel and titanium, as well as materials that can wear out such as metal matrix composites (MMCs), tool wear has been noted to be a serious issue in such circumstances [6]. Hence, based on type of substrate material to be welded tool material will be selected. Table 1

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shows the most commonly used tool materials for different base materials and thicknesses [8].

Table 1: FSW tool materials

Alloys to be welded	Thickness (mm)	Tool material
Aluminium alloys	3-50	Tool steels, Co-WC composite
Magnesium alloys	3-10	Tool steel, WC composite
Copper alloys	3-50	Ni-alloys, W-alloys, PCBN, Tool steels
Titanium alloys	3-10	W-alloys
Stainless steels	3-10	PCBN, W-alloys
Low-alloy steels	3-10	WC composite, PCBN
Nickel alloys	3-10	PCBN

V. WELDING PARAMETERS

FSW involves complex material movement and plastic deformation. Welding parameters, tool geometry, and joint design exert significant effect on the material flow pattern and temperature distribution, thereby influencing the microstructural evolution of the material [9]. Therefore, welding speed, the tool rotation speed, the tilt angle of the tool, tool material and tool design are the main independent variables that are used to control the FSW process [2]. The main process parameters and their effects in FSW are shown in Table 2 [20].

Table 2: FSW parameters

Parameter	Effects of parameter
Rotational speed (rpm)	Frictional heat, stirring, oxide layer breaking and mixing of material
Traverse speed (mm/min)	Appearance, heat control
Plunge depth (mm)	Frictional heat, maintaining contact conditions
Tilting Angle (°)	The appearance of the weld, thinning

1) Tool Design

The design of the tool is a critical factor in FSW as a good tool can improve both quality of the weld and the maximum possible welding speed. Tool design influences heat generation, plastic flow, the power required, and the uniformity of the welded joint. Tool geometry such as probe length, probe shape and shoulder size are the key parameters because it would affect the heat generation and the plastic material flow [10]. Important design parameters include shoulder design and pin or probe profile design.

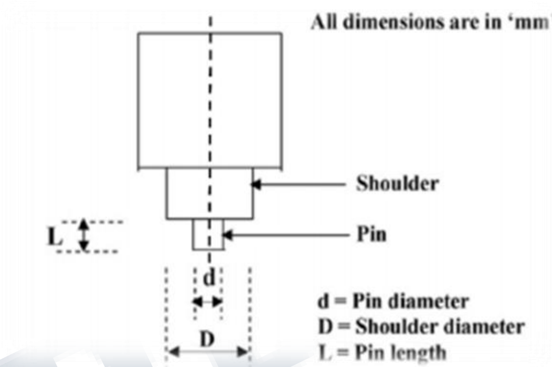

Fig. 2: FSW tool dimensions

a) Shoulder surface design

The diameter of the tool shoulder is important because the shoulder generates most of the heat, and its grip on the plasticized materials largely establishes the material flow field. Both sliding and sticking generate heat whereas material flow is caused only from sticking. For a good FSW practice, the material should be adequately softened for flow, the tool should have adequate grip on the plasticized material and the total torque and traverse force should not be excessive [6].

Fig. 3 summarises the typical shoulder outer surface and the bottom end surface features. The shoulder outer surface usually has a cylindrical shape, but occasionally, a conical surface is also used. Generally it is expected that the shape of the shoulder outer surface has an insignificant influence on the welding quality because the shoulder plunge depth is typically small [11].

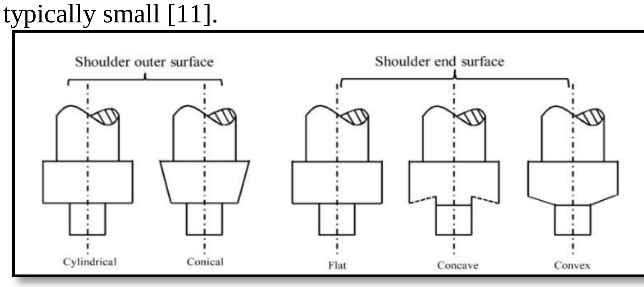

Fig. 3: Shoulder surfaces

Among three different types of shoulder end surfaces, the flat shoulder end surface is of the simplest design. The main disadvantage of this design is that the flat shoulder end surface is not effective for trapping the flowing material under the bottom shoulder that leads to the

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production of excessive material flash. For this reason, a concave shoulder end surface is designed for restricting material extrusion from the sides of the shoulder. During tool plunging, the material displaced by the probe is fed into tool shoulder cavity. Hence the concave surface profile of the tool shoulder serves as an escape volume or reservoir for the displaced material from the probe. Another possible end shape of the shoulder is a convex profile provides an advantage that it can attain contact with the work-piece at any location along the convex end surface, and thereby accommodate differences in flatness or thickness between the two adjoining work-pieces.

b) Pin profile design

The profile of the pin (or probe) plays a crucial role in plasticized material flow, in turn regulates the welding speed of the FSW process and affects weld properties. Five different pin profiles are shown in figure 4 [12].

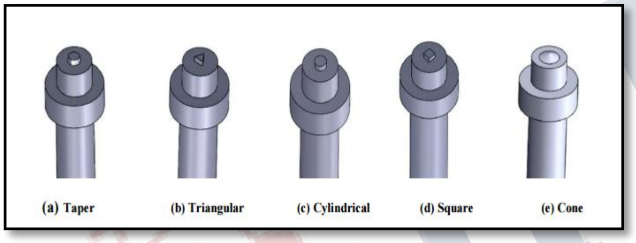

Fig. 4: Pin profiles

FSW probes usually have a cylindrical outer surface but a tapered outer shape of different profiles can also be used as indicated in the fig. 4. In particular, cylindrical probes have been widely used for joining plates up to 12mm thick. With the tapered probes, the higher frictional heat increases the plastic deformation because of the larger contact area of the probe with the work-piece. The tapered probes also promote a high hydrostatic pressure in the weld zone, which is extremely important for enhancing the material stirring. However, the high temperature hydrostatic pressure may lead to severe tool wear.

The probe outer surface can have different shapes and features including threads, flats or flutes. Thread-less probes are chosen for high strength or high abrasive alloys as the threaded features can be easily worn away [11].

B. Tool rotation and Traverse speed

In FSW, two tool speeds are to be considered; namely, the tool rotation speed and the traverse speed (or welding speed). This is because the cylindrical tool must turn to generate heat on the joint and then traverse the length of the joint transmitting that heat. These two parameters have considerable importance as they ensure a successful and efficient welding cycle. The relationship between the rotational speed and welding speed is complex but, in general increasing rotational speed or decreasing traverse speed results in a hotter weld, but they are not mutually exclusive. Typically a friction stir tool rotates within the range of 200 to 2000 rotations per minute (rpm). The average traverse rate of the tool along the joint line is between 10 to 500 millimetres per minute (mm/min). The speeds are largely determined by the type of alloy, plunge penetration depth and joint type.

Higher tool rotation generates higher temperature because of higher frictional heating and result in more intense stirring and mixing of material. During traversing, softened material from the leading edge due to the tool rotation and the traverse movement of the tool, and this transferred material, are consolidated in the trailing edge of the tool by the application of an axial force [2].

C. Tool tilt and Plunge depth

The tool is usually characterized by a small tilt angle (θ). The tilt of the cylindrical tool can have major effects on the welding process. A general range for tool tilt is between 2 to 4 degrees, in such a way that the tool leans into the joint. A minor tilt can affect the ease with which the tool can move across the joint line because less pressure is put in the direction of the joint line.

A suitable tilt of the spindle towards trailing direction ensures that the shoulder of the tool holds the stirred material by threaded pin and move material efficiently from the front to the back of the pin [9]. The plunge depth is defined as the depth to which the shoulder of the tool sinks into the material, while the pin extends further in this distance; friction creates the heat necessary to plasticize the basematerial. Plunging the shoulder below the plate surface increases the pressure below tool and helps ensure adequate forging of the material at the rear of the tool.

Higher plunge depth would increase the heat generation by tool shoulder and plasticized volume of the stir zone and thereby improving the joint strength. The plunge depth has the greatest influence on the tensile shear strength of the joints [13].

VI. PROCESS PARAMETER OPTIMIZATION

Process optimization of FSW is done through various methods such as feasibility study, Taguchi technique, Artificial Neural Network, Response Surface Methodology, Mathematical modelling, Thermo-mechanical

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modelling, and others. Optimization of FSW includes arriving at the best combination of process parameters that ensures most effective and high quality weld joints and weld properties. The optimal combination of parameters is not same for all types of material combinations. However, it is found from many researchers that, higher tool rotational speed, higher welding speed and lower axial force are preferred to produce a better quality of weld without internal defects.

Optimization of process parameters results in:

1. Improved mechanical properties such as Yield strength, Ultimate tensile strength, and Hardness.
2. Refined grain structure.
3. Reduced friction weld defects such as wormholes and surface imperfections.

VII. APPLICATIONS

Since the repeatable quality of the solid phase welds can improve existing products and lead to a number of new product designs previously not possible, FSW has various industrial applications. A few such important industries include,

1. ***Shipping and marine industry*****:** Manufacturing of hulls, offshore accommodations, aluminium extrusions, decks, sides, bulkheads, masts and booms, refrigeration plant, etc.
2. ***Aerospace industry*****:** For welding of wings, fuselages, empennages, cryogenic fuel tanks, Al alloy fuel tanks for space vehicles, manufacturing of wings, military and scientific rocket bodies, etc.
3. ***Railway industry*****:** Building of container bodies, rolling stock of railways, underground carriages, railway tankers, container bodies, etc.
4. ***Land transport:*** Manufacture of engine and chassis cradles, body frames, wheel rims, truck bodies, tail lifts for Lorries, articulated lifts and personnel bridges, window frame, pipe fabrication, etc.
5. ***Electrical industry:*** Electric motor housings, bus-bars, electrical connectors, encapsulation of electronics, etc.

VII. FUTURE PROSPECT

FSW has been a major boon to advanced industry since its inception. In spite of its short history, it has found widespread applications in diverse industries. Hard materials such as steel and other important engineering alloys can now be welded efficiently using this process. The future scope of work is extendable to:

1. Develop FSW that produces defect free welds of uniform weld properties.
2. The applicability of FSW to new Engineering alloys.
3. Focus on thermo-mechanical phenomenon.
4. Substitute the conventional joining technologies with low costs and high efficient process.

VIII. CONCLUSION

FSW is a revolutionary technology with enormous growth potential due to its inherent benefits. It has a tremendous impact on joining technology owing to its unique characteristics such as low distortion and shrinkage even in long welds. Further, free of arc, filler metal, shielding gas, low heat affected zone, free of spatter and porosity defect are its vital positive attributes. FSW is the best process to weld different alloys of aluminium with an excellent quality. Considerable effort is being made to weld higher temperature materials such as alloys of magnesium, titanium and steels by using FSW. The process is more flexible since it is used to produce different joint configurations. Some important conclusions that are drawn from this review include:

1. FSW is a solid state joining process that is capable of welding both similar and dissimilar metals.
2. FSW can weld alloys considered conventionally un-weldable.
3. Careful control of processing parameters is required to obtain optimized welds.
4. FSW has many applications in various industries including aerospace, nuclear, transportation and defence.

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