EVALUATION OF PARAMETERS OF FRICTION STIR WELDING FOR ALUMINIUM AA6351 ALLOY

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Abstract

Friction Stir Welding (FSW) is a solid state welding process in which the relative motion between the tool and the work piece produces heat which makes the material of two edges being joined by plastic atomic diffusion. This method relies on the direct conversion of mechanical energy to thermal energy to form the weld without the application of heat from conventional source. The rotational speed of the tools, the axial pressure and welding speed and the (weld time) are the principal variables that are controlled in order to provide the necessary combination of heat and pressure to form the weld. These parameters are adjusted so that the interface is heated into the plastic temperature range (plastic state) where welding can take place. During the last stage of welding process, atomic diffusion occurs while the interfaces are in contact, allowing metallurgical bond to form between the two materials. The functional behaviour of the weldments is substantially determined by the nature of the weld strength characterized by the tensile strength, metallurgical behavior, surface roughness, weld hardness and micro hardness. In this project an attempt is made to determine and evaluate the influence of the process parameters of FSW on the weldments. The Vickers hardness, tensile strength and radiography are considered for investigation by varying tool speed, tool feed and maintaining constant depth of penetration of weld. Experiments were conducted on AA6351 Aluminium alloy in a CNC Vertical Machining Centre. The output factors are measured in UTM, Vickers hardness tester and Radiography equipment. Results show strong relation and robust comparison between the weldment strength and process parameters. Hence FSW process variable data base is to be developed for wide variety of metals and alloys for selection of optimum process parameters for efficient weld.

Keywords: Friction stir Welding, Atomic Diffusion, AA6351 Aluminium alloy, Vickers hardness, Tensile Strength

1. Introduction

Friction Stir Welding (FSW) is a solid state welding process first discovered and patented by the Welding Institute of Cambridge U.K. in 1991 by Wayne Thomas et al. and has been since then the subject of a great deal of interest. As per a survey done by Prof. A. P. Reynolds, Guest Editor of Science and Technology of Welding and Joining journal, since 1996, more than 5% of all refereed journal articles related to welding have been friction stir welding articles and if the friction stir processing literature is included this number is even greater.FSW is a solid state joining process that uses friction generated by a rotating cylindrical tool to heat and plasticize metal on either side of a joint, creating a solid, functional weld. Friction-generated heat is more effective at reorganizing the microstructure of metals and metal alloys than other forms of fusion welding, but FSW can be a much slower process. The process uses a rotating, non-consumable weld tool that plunges into the base material and moves forward. Friction heat caused by the rotating pin creates a plasticized tubular shaft around the pin. Pressure provided by the weld tool forces the plasticized material to the back of the pin, cooling and consolidation. Al alloy is difficult to weld by traditional methods, due to high thermal conductivity, resulting in defects like porosity, cracks etc. Hence FSW is being increasingly used. The process is especially well suited to butt and lap joint in aluminium since aluminium is difficult to weld by arc process, but is very simple to weld by FSW.

2. Principle of Operation - Friction Stir welding

This welding technique involves the joining of metals without fusion or filler materials. It is used already in routine, as well as critical applications, for the joining of structural components made of aluminium 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. 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 work piece. There is a volumetric contribution to heat generation from the adiabatic heating due to deformation near the pin. The welding parameters have to be adjusted so that the ratio of frictional to volumetric deformation--induced heating decreases as the work piece becomes thicker. This is in order to ensure a sufficient heat input per unit length.

The micro structure of friction stir welding 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 recrystallize, so that the detailed microstructure may consist of equated grains. The layered (onion-ring) structure is a consequence of the way in which a threaded tool deposits material from the front to the back of the weld. It seems that cylindrical sheets of material are extruded during each rotation of the tool, which on a weld cross--section gives the characteristic onion-rings.

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.

2.1 Friction Stir Welding Process 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 micro structural evolution of material. In this section, a few major factors affecting FSW/FSP process, such as tool geometry, welding parameters, joint design are addressed. The strength of Friction stir welding depends on the following three process parameters. They are

1. Spindle speed
2. Feed rate
3. Depth of penetration

2.1.1 Spindle Speed:

The spindle speed is the rotational frequency of the spindle of the machine, measured in revolutions per minute (RPM). The preferred speed is determined based on the material being cut. Excessive spindle speed will cause premature tool wear, breakages, and can cause tool chatter, all of which can lead to potentially dangerous conditions. Using the correct spindle speed for the material and tools will greatly affect tool life and the quality o the surface finish. The speed at any point on the periphery (outside edge) of a cutter must always be equal to the ideal speed for the material for it to work at its optimum performance. The spindle speeds may be calculated for all machining operations once the welding speed is known. The best speed depends on the following conditions:

1. Weld strength and quality of the weldment required - Higher quality of weld and strength can be obtained at high speed operations.

2. Material to be welded - Hard material requires high speed operation.

3. Size of weld. Large welds require low speed operation.

4. Thickness of the work piece to be welded.

2.1.2 Feed Rate

Feed rate is the velocity at which the cutter is fed, that is, advanced against the work piece. It is expressed in units of distance per revolution for turning and boring (typically inches per revolution (ipr) or millimeters per revolution). It can be expressed thus for milling also, but it is often expressed in units of distance per time for milling (typically inches per minute (ipm) or millimeters per minute).

3. Welding Parameters

For FSW, two parameters are very important: tool rotation rate (v, rpm) in clockwise or counter clockwise direction and tool traverse speed (n, mm/min) along the line of joint. The rotation of tool results in stirring and mixing of material around the rotating pin and the translation of tool moves the stirred material from the front to the back of the pin and finishes welding process. Higher tool rotation rates generate higher temperature because of higher friction heating and result in more intense stirring and mixing of material as will be discussed later. However, it should be noted that frictional coupling of tool surface with work piece is going to govern the heating. So, a monotonic increase in heating with increasing tool rotation rate is not expected as the coefficient of friction at interface will change with increasing tool rotation rate. The ratio of influence of tool speed and weld speed is 4: 3 which was found by experimental results.

In addition to the tool rotation rate and traverse speed, another important process parameter is the angle of spindle or tool tilt with respect to the work piece surface. 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. Further, the insertion depth of pin into the work pieces (also called target depth) is important for producing sound welds with smooth tool shoulders. The insertion depth of pin is associated with the pin height. When the insertion depth is too shallow, the shoulder of tool does not contact the original work piece surface. Thus, rotating shoulder cannot move the stirred material efficiently from the front to the back of the pin, resulting in generation of welds with inner channel or surface groove. When the insertion depth is too deep, the shoulder of tool plunges into the work piece creating excessive flash. In this case, a significantly concave weld is produced, leading to local thinning of the welded plates. It should be noted that the recent development of ‘scrolled’ tool shoulder allows FSW with 08 tool tilt. Such tools are particularly preferred for curved joints.

Preheating or cooling can also be important for some specific FSW processes. For materials with high melting point such as steel and titanium or high conductivity such as copper, the heat produced by friction and stirring may be not sufficient to soften and plasticize the material around the rotating tool. Thus, it is difficult to produce continuous defect-free weld. In these cases, preheating or additional external heating source can help the material flow and increase the process window. On the other hand, materials with lower melting point such as aluminium and magnesium, cooling can be used to reduce extensive growth of recrystallized grains and dissolution of strengthening precipitates in and around the stirred zone.

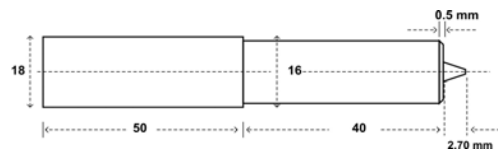
4. Experimental Procedure

4.1 *Selection of material*

Aluminum Alloy AA6351: Aluminium alloy AA6351 is a medium Strength alloy with excellent corrosion Resistance. It has the highest strength of the 64430 series alloys. Alloy AA6351 is known as a structural alloy. In plate form, AA6351 is the alloy most commonly used for machining. . The addition of a large amount of manganese controls the Grain structure which in turn results in a stronger alloy. Alloy AA6351 machines well and produce tight coils of swarf when chip breakers are used.

4.2 *Tool material:* High speed steel (Wc-Co)

4.3 *Tool dimensions:*



4.4 *Sample Preparation*

Rolled plates of 6mm in thickness were cut into the required size (120mm x 60 mm x 6 mm) by power hacksaw cutting and milling. The experiments were conducted on the aluminium alloy IS 64430. Before the friction welding, the weld surface of the base material was cleaned. Plate edges to be weld were also prepared so that they are fully parallel to each other. This is to ensure that there is no uneven gap between the plates which may not result in sound welding. Secondly surface preparation was also done so that the surfaces of both the plates are of equal level and footing.

4.5 *Experiment*

A CNC milling machine was used for friction stir processing (FSW) of aluminum alloy. The machine was a maximum speed of 6000 rpm and 10-horse power. Test piece was clamped in the fixture tightly. Initially the rotating pin was inserted into a predrilled hole, which will facilitate the start up of welding. Tool tilt angle was 2^o. Processing began at spindle speed of 770 rpm and travel rate of 75mm/min. the speed was increased by 130rpm every pass up to a final speed of 900rpm.Since tool plunge was to the extent of 3 mm and plate thickness being 6 mm, the same step was repeated for both sides of the plate. The result was two side welded plates. The process was repeated for tool travel rate of 90 mm/min for the tool speeds of 900 rpm. The plates where then subjected to mechanical testing.

In the present work the influence of speed, feed on the performance of FSW such as Hardness and tensile strength is evaluated at different experimental conditions.

5. Results and Discussions

Rotational speed was 770 rpm with weld speed of 75 mm/min. double side welding was carried out i.e. both sides welding was carried out. Similarly welding was carried out for different rotational speeds of 900rpm but with weld speed of 90 mm/min. again here also double side welding was done. Thus, Aluminium IS 64430 Al alloy joints were welded successfully by friction welding process using two different rotational speeds. Some interesting developments of mechanical properties have been found to occur in the weldments. The tensile testing of the weld and Vickers hardness number is influenced by the rotational speed and feed of the tool. The effects of tool rotation speeds and feed towards the tensile testing and Vickers hardness of the joints were investigated. The results of the tests are shown in graphs below for the specimen prepared using friction welded joints obtained at the two rotational speeds mentioned below

Work Piece No.	Rotational Speed (rpm)	Feed (mm/min)	Weld Condition
1	700	75	Double Side
2	900	90	Double Side
3	1150	108	Double Side
4	1350	115	Double Side

Table-1: Different speeds at different feeds performed on Specimen

5.1 *Hardness Test*

Vickers Hardness Test (Double Side Welding)

The results obtained during double side welding are plotted against the rotational speed of the spindle (FSW Tool) of 900rpm and weld speed of 90 mm/min. It is observed that the Hardness is minimum at the weld centre i.e. at the centre of the weld nugget. Hardness values reduced at the centre weld then parent metal shown in table below.

S. No	Speed (rpm)	Feed (mm/min)	Vickers Hardness No (1 kg loading for 10 sec)
1	700	75	85
2	900	90	88.5
3	1150	108	88.9
4	1350	115	90.2
Parent metal			93.5

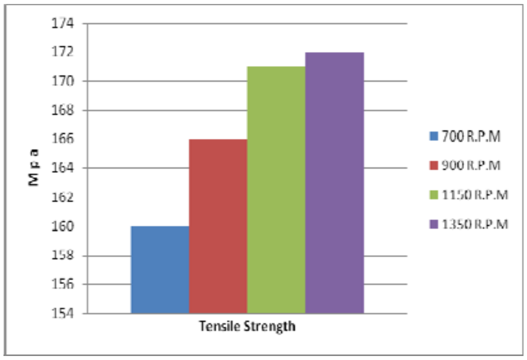
Table- 2: Hardness observations

5.2 *Tensile strength Test*

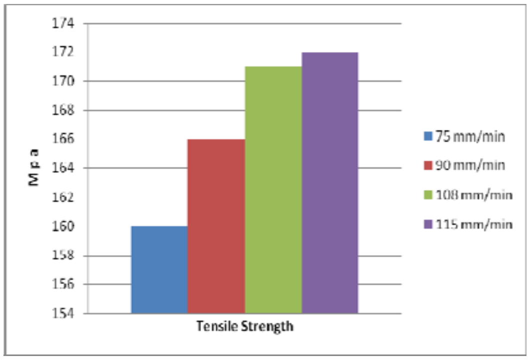
In both the above cases, Increase in rotational speed has resulted in increase of tensile strength. Primary reason is that higher the speed, higher will be the deformation and heat generation in the weld. This will result in finer grain structures, because of which tensile strength is increases. The results of tensile test which were observed during the experiment were tabulated which are shown in below

S.No	Speed (rpm)	Feed (mm/min)	Tensile Strength (MPa)
1	700	75	160
2	900	90	166
3	1150	108	171
4	1350	115	172
Base Material			250

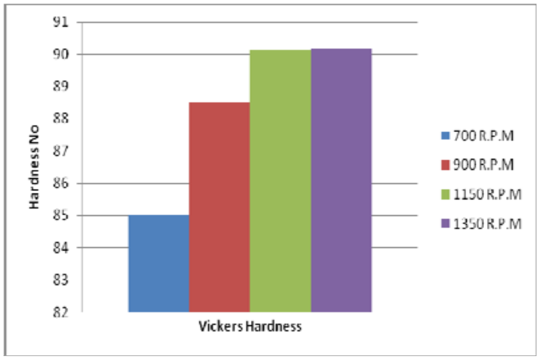
Table-3: Tensile strength observations



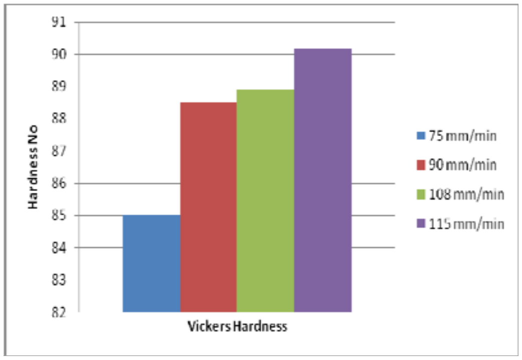
Graph 1: Speed v/s Tensile strength



Graph 2: Feed V/s Tensile strength



Graph 3: Speed v/s Hardness



Graph 4: Feed Vs Hardness

5.3 *Radiography Test Results*

The results of radiography test which were observed during the experiment were tabulated which are shown in below:

S.No	Test parameter	Results
1	Radiography test	No significant defect indications are noticed. Hence acceptable.

Table-4: Radiographic observations

6. Conclusions

1. Vickers hardness of the weldment is 85 as of 93.5 of parent metal; therefore the weldment is weaker than parent metal due to misalignment of welding line & tool.

2. Alignment of work piece welding line and tool is an important factor to be considered to obtain high tensile strength. In experimental work, it has been observed that due to misalignment of welding line and tool, the tensile strength is lower that is 160 MPa when compared to the same work with proper alignment (274Mpa)

3. Pure aluminium alloy cannot be friction stir welded due to its high thermal conductivity and low melting point as it is observed while conducting the experiment.
4. Tensile strength is found to increase with increase in rotational speed. Maximum Tensile strength of 172 Mpa was observed at 1350 rpm (for 115 mm/min feed). This indicates that for IS 64430 AA6351 Al alloys, higher range of rotational speed is best suited to achieve maximum tensile strength.

5. High surface finish is obtained at tool speed of 1350 rpm and weld speed of 115 mm/min

6. Tensile strength is higher with lower weld speed. This indicates that lower range of weld speed is suitable for achieving maximum tensile strength.

7. No filler metals and external source of heat (arc, gas) was used while performing the experiment, hence adoptable as no exhaustible resources are involved.

8. Friction stir welding being and eco friendly metal joining process which is the need of the hour should be implemented to avoid environmental related problems.

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