International Journal of Advance Research in Science and Engineering
Vol. No.6, Issue No. 05, May 2017
www.ijarse.com
IJARSE
ISSN (O) 2319 - 8354
ISSN (P) 2319 - 8346

A CRITICAL REVIEW ON OPTIMIZATION OF PROCESS PARAMETERS OF FRICTION STIR WELDING

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ABSTRACT

Friction Stir Welding (FSW), being a novel process and facilitates welding various joints required for several industries mainly aerospace, marine, spacecraft, automotive, etc. It is an attractive solid state material joining technology, different to conventional welding methods, having ability to produce welds with higher integrity and minimum induced distortion, reduced porosity defect, reduced heat affected zone, no requirement of shielding gas, ecofriendly and minimum residual stresses etc. In this paper, a critical estimation of important features of friction stir welding namely process principle, selection of tool and workpiece material, metallurgical and mechanical aspects; effect of process parameters; methodology for optimizing the process parameters have been discussed. Further different applications of the process are presented along with critical review of literature; finally recognized areas of research work on materials such as AA6061 and Taguchi (L9) orthogonal array used as a methodology to optimize the process parameters for conditions to achieve better quality welds.

Keywords: Aluminum alloy 6061, Friction Stir Welding, L9 Orthogonal array, Review and Taguchi.

I. INTRODUCTION

Friction stir welding was invented at the welding institute of UK in 1991 as a solid-state joining technique, and it was initially applied to aluminum alloys. [1] Alloys of this class are extensively employed in marine frames, pipelines, and storage tanks and aircraft applications. Compared to many of the fusion welding processes that are normally used for joining structural alloys, FSW is an emerging solid state joining process in which the material that is being welded is not melted and recast. It is also an effective joining technique for a variety of different materials. The metals with low melting temperatures such as copper and aluminum were among the first to be joined by this technique with the help of steel tool. Mahoney et al. [2] found that joints formed by FSW hold much of the base material strength and have many other advantages over joints produced by conventional welding techniques. Chao et al. [3] found that the maximum temperature in the material being welded is usually less than 80% of its melting temperature of the base metal. Hence, the welding defects like

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ISSN (O) 2319 - 8354
ISSN (P) 2319 - 8346

distortion, solidification, cracking, porosity, oxidation, and other defects that result from conventional fusion welding are not observed [4-5].

II. WORKING PRINCIPLE

Friction stir welding (FSW) is a solid-state joining technique in which coalescence occurs due to thermo mechanical deformation of workpieces as the resulting temperature exceeds the solidus temperature of workpieces. The fundamental concept of FSW technique is depicted in Fig.1. It consists of a non-consumable rotating tool having a specially designed tool pin and shoulder. Tool pin is plunged into the faying faces of sheets or plates to be joined thus tool moves in the transverse direction along the length. The tool rotates in the clockwise direction and translates from front to back as shown in Figure 1. The left side where the direction of tool rotation is same of tool travel direction is termed as advancing side. It is opposite to the direction of metal flow. The side opposite to advancing side where rotation of tool is reverse of direction of tool travel is termed as retreating side. Due to frictional heat between tool and workpiece, material around the pin is softened and a solid state joint is produced without melting. [6-7]

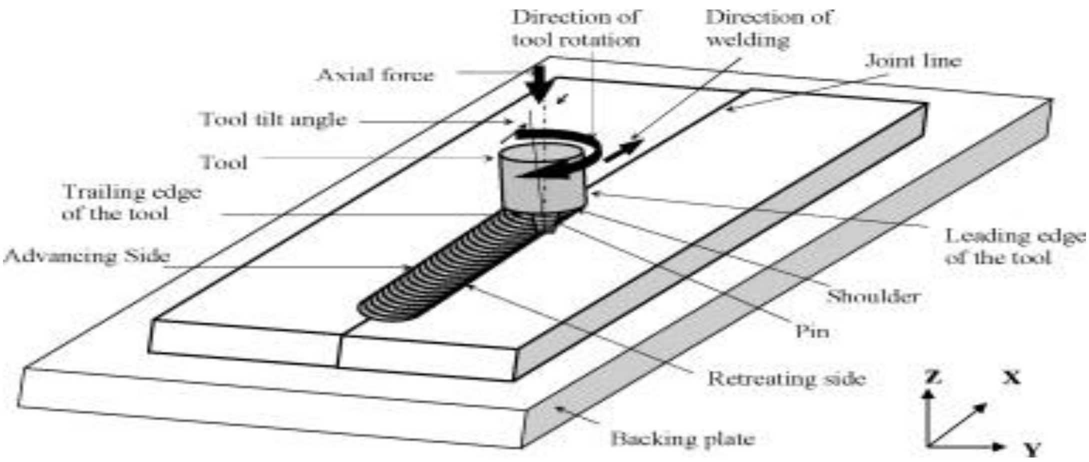

Figure 1: Schematic representations of friction stir welding.[11]

In FSW joints various micro structural regions can be observed as shown in Fig. 2. The Base metal region is unaffected by heat as it is far away from the recrystallized zone and hence micro structural and mechanical properties of this region remains unaltered. The second region is heat-affected zone (HAZ) that is next to Base metal and is affected by heat but no plastic deformation takes place in this region; however, mechanical and micro structural properties changes. The next region is thermo mechanically affected zone (TMAZ) affected zone that is very near to weld nugget and it is plastically deformed by means of tool. In this region material deforms without recrystallization. Next region is nugget zone or stir zone or fully recrystallized zone in which tool pin rotates and produces frictional heat; results in severe plastic deformation. [8-9]

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ISSN (P) 2319 - 8346

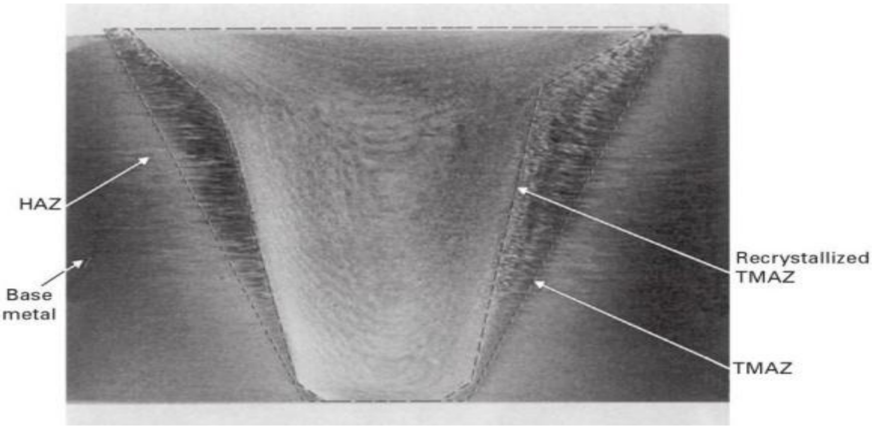

Figure 2: FSW transverse section (Misra & Ma, 2005)

III. THE CRITICAL WELDING PARAMETERS

3.1 Tool Rotation and Traverse Speeds, to be considered in FSW; how fast the tool rotates and how quickly it traverses the interface. These two parameters have considerable importance and must be chosen with care to ensure a successful and efficient welding cycle. Further, the relation with heat input is complex, increasing the rotation speed or decreasing the traverse speed will result in a hotter weld also for good weld quality, and material surrounding the tool should be hot enough to enable the extensive plastic flow required and minimize the forces acting on the tool leading to tool breakage. On the other hand excessively high heat input may be detrimental to the final properties of the weld.

3.2 Tool tilt and plunge depth, plunge depth is defined as depth of the lowest point of the shoulder below the surface of the welded plate and plunging the shoulder below the plate surface increases the pressure below the tool and helps ensure adequate forging of the material at the rear of the tool. Tilting the tool by 1 to 4 degrees, such that the rear of the tool is lower than the front, will assist this forging process. This will ensure the necessary downward pressure such that the tool fully penetrates the weld addressing defects such as pin rubbing on the backing plate surface or a significant under match of the weld thickness compared to the base material etc.

3.3 Tool Design, good tool can improve both quality of the weld and the maximum possible welding speed. So it is desirable that the tool material is sufficiently strong, tough, and hard wearing at the welding temperature along with good oxidation resistance and low thermal conductivity. For example tool steel AISI H13 and HSS M2 to weld aluminum alloys within thickness ranges of 0.5 – 50 mm but more advanced tool materials are necessary for more demanding applications such as highly abrasive metal matrix composites or higher melting point materials such as steel or titanium. Majority of tools have a concave shoulder profile.

3.4 Welding forces, a number of forces will act on the tool during welding, a downward force to maintain the position of the tool, the traverse force acts parallel to the tool motion, and torque is required to rotate the tool. In order to prevent tool fracture and to minimize excessive wear and tear on the tool and associated machinery, the welding cycle is to be modified by finding the best combination of welding parameters.

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ISSN (O) 2319 - 8354
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3.5 Flow of material, mode of material flow through extrusion chamber and frozen pin technique will lead to better forging of material.

IV. LITERATURE REVIEW

Ericsson and Sandstrom (2002) studied the influence by welding speed on the fatigue strength of friction stir welds and also compare the fatigue results with results for conventional arc-welding methods: MIG-pulse and TIG. Aluminum alloy 6082 used as a working materials.

Liu et al. (2003) studied the optimum welding parameters of friction stir welding on AA2017-T35 to establish the relations between welding parameters and tensile strength of the joints.

Kovacevic (2003) investigate a three-dimensional model based on finite element analysis was used to study the thermal history and thermo mechanical process in the butt-welding of aluminum alloy 6061-T6.

Huseyin Uzun et al.(2004) studied microstructure, hardness and fatigue properties of friction stir welded joint of dissimilar Al 6013-T4 alloy and X5CrNi18-10 stainless steel. Optical microscopy was used to characterize the microstructures of the weld nugget, the heat affected zone (HAZ), and thermo-mechanical affected zone (TMAZ) and the base materials.

Cavaliere et al. (2005) studied the mechanical and micro structural properties of weld joint of dissimilar 2024 and 7075 aluminum sheets joined by friction stir welding (FSW) and analyze the mechanical response with respect to the parent materials.

Kovacevic (2005) studied thermo-mechanical simulation of friction stir welding to predict the transient temperature field, active stresses developed forces in all the three dimensions and may be extended to determine the residual stress.

Marzol et al. (2006) established that friction stir welding (FSW) process parameters envelope for an AA 6061 alloy reinforced with 20% of Al_2O_3 particles, and also determine the properties of the obtained joints. Microstructure has been observed with optical microscope, and images have been analyzed with image analysis software.

Watanabe et al. (2006) investigated the effects of a pin rotation speed, the position for the pin axis, on the tensile strength and the microstructure of the joint. The behaviour of the oxide film on the faying surface of the steel during welding also examined.

Scialpi et al. (2006) studied the effect of different shoulder geometries on the mechanical and micro structural properties of a friction stir welded joints of aluminum alloy 6082 T6. The effect of the three shoulder geometries has been analyzed by visual inspection, macrograph, HV micro hardness, bending test and transverse and longitudinal room temperature tensile test. The investigation results showed that, for thin sheets, the best joint has been welded by a shoulder with fillet and cavity.

Zhang et al. (2007) represent the 3D material flows and mechanical features under different process parameters by using the finite element method based on solid mechanics. Experimental results were also given to study the effect of process parameters on joining properties of the friction stir welds. Numerical results indicate that the tangent flow constitutes the major part in the material flow. The shoulder can accelerate the material flow on the top half of the friction stir welding.

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Cavalierea et al. (2007) analyzed the effects of processing parameters on mechanical and micro structural properties of AA6082 joints produced by friction stir welding. Different welded specimens were produced by employing fixed rotating speeds of 1600rpm and by varying welding speeds from 40 to 460 mm/min. The SEM observations of the fatigue specimens, welded at 115 mm/min, showed that at higher stress amplitude levels the cracks initiate at the surface of the welds. By decreasing the stress amplitude the cracks initiate by the internal defects.

Elangovan et al. (2007) studied the influences of tool pin profile and welding speed on the formation of friction stir processing zone in AA2219. In this investigation an attempt has been made to study the effect of tool pin profiles and welding speed on the formation of friction stir processing zone in AA2219.

Moreira et al. (2008) Studied that mechanical and metallurgical characterization of friction stir welded butt joints of aluminum alloy 6061-T6 with 6082-T6 was carried out. For comparison, similar material joints made from each one of the two alloys were used. The work included microstructure examination, micro hardness, tensile and bending tests of all joints. The results show that the friction stir welded dissimilar joint present intermediate mechanical properties when compared with each base material. In tensile tests the dissimilar joint displayed intermediate properties. For instance in the hardness profile the lowest values were obtained in the AA6082-T6 alloy plate side where rupture occurred, and in the nugget all type of joints present similar values.

Kanwer S. Arora et al. (2010) studied that friction stir welding of aluminum alloy 2219 using an adapted milling machine was reported. The downward or forging force was found to be dependent upon shoulder diameter and rotational speed whereas longitudinal or welding force on welding speed and pin diameter. Tensile strength of welds was significantly affected by welding speed and shoulder diameter whereas welding speed strongly affected percentage elongation.

Hwang et al. (2010) experimentally explore the thermal history of a work piece undergoing Friction Stir Welding involving butt joining with pure copper C11000. In the experiments, K-type thermocouples were used to record the temperature history at different locations on work piece. This data, combined with the preheating temperature, tool rotation speeds and tool moving speeds allowed parameters for a successful weld to be determined.

S. Rajakumar et al. (2011) observed that in FSW process tool parameters plays a major role in deciding the joint strength. Joint strength is influenced by grain size and hardness of the weld nugget region. Hence, in this investigation an attempt was made to develop empirical relationships to predict grain size and hardness of weld nugget of friction-stir-welded AA6061 aluminum alloy joints. The empirical relationships are developed by response surface methodology incorporating FSW tool and process parameters. A linear regression relationship was also established between grain size and hardness of the weld nugget of FSW joints.

Aval (2011) investigate that the thermo-mechanical responses during the dissimilar friction stir welding of aluminum alloys have been evaluated employing a three-dimensional model and the finite element software ABAQUS. Also, both experimental and simulated results indicate that welding fixtures significantly affect the residual stress profiles as well as their magnitudes.

Elangovan et al. (2012) focuses on the development of an effective methodology to determine the optimum welding conditions that maximize the strength of joints.

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ISSN (O) 2319 - 8354
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Mariano et al. (2012) presents a literature review on friction stir welding (FSW) modeling with a special focus on the heat generation due to the contact conditions between the FSW tool and the work piece. A reliable FSW process modeling depends on the fine tuning of some process and material parameters. Usually, these parameters are achieved with base on experimental data. The numerical modeling of the FSW process can help to achieve such parameters with less effort and with economic advantages.

Zhang (2012) studied that, the thermal modeling of underwater friction stir welding (FSW) was conducted with a three-dimensional heat transfer model. The vaporizing characteristics of water were analyzed to illuminate the boundary conditions of underwater FSW. Temperature dependent properties of the material were considered for the modeling. For underwater joint, the high-temperature distributing area is dramatically narrowed and the welding thermal cycles in different zones are effectively controlled in contrast to the normal joint.

Bhatt (2013) observed that Friction stir welding of AA6061-T6 aluminum alloy to overcome limitations of fusion welding. The FSW tool, not being consumed, produces a joint with predominant advantages of high joint strength, lower distortion and absence of metallurgical defects. Process parameters such as tool rotational speed, tool traverse speed and axial force and tool dimensions play an important role in obtaining a specific temperature distribution and subsequent viscosity distribution within the material being welded.

Guo (2013) Studied that the Dissimilar AA6061 and AA7075 alloy have been friction stir welded with a variety of different process parameters. In particular, the effects of materials position and welding speed on the material flow, microstructure, micro hardness distribution and tensile property of the joints were investigated. It was revealed that the material mixing is much more effective when AA6061 alloy was located on the advancing side and multiple vortexes centers formed vertically in the nugget.

Keivani (2013) have studied in their work, friction stir welding (FSW) is applied extensively in industry for joining of nonferrous metals especially aluminum. A three-dimensional model based on finite element analysis was used to study the thermal characteristic of copper C11000 during the FSW process.

Liu a (2013) In their research, the 4 mm thick 6061-T6 aluminum alloy was self-reacting friction stir welded at a constant tool rotation speed of 600 rpm.The specially designed self-reacting tool was characterized by the two different shoulder diameters. The results of transverse tensile test indicated that the elongation and tensile strength of joints increased with increasing welding speed. The defect-free joints were obtained at lower welding speeds and the tensile fracture was located at the heat affected zone adjacent to the thermal mechanically affected zone on the advancing side.

Simoes a, (2013) studied the FSW of polymers, From the study it was possible to conclude that, due to the polymers rheological and physical properties, the thermo-mechanical conditions during FSW are very different from that registered during welding of metals, leading to completely different material flow mechanisms and weld defect morphologies.

Pan (2013) studied that friction Stir Welding is a complex thermal-mechanical process. Numerical models have been used to calculate the thermal field, distortion and residual stress in welded components but some modeling parameters such as film coefficient and thermal radiation of the work pieces may be technically difficult or expensive to measure experimentally. By comparing the FEM numerical results with experimental results, the

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ISSN (O) 2319 - 8354
ISSN (P) 2319 - 8346

FSW process thermal parameters have been successfully identified. This automatic parameters characterization procedure could be used for the FSW process optimization.

He (2014) discussed and illustrated numerical analysis of friction stir welding with brief case studies. In addition, several important key problems and issues remain to be addressed about the numerical analysis of friction stir welding and opportunities for further research are identified.

V. RESULTS AND DISCUSSION

From the above literature study it is evident that there is a potential for Friction Stir Welding of aluminum alloys in various fields. FSW continues to be the subject of investigations and further development and improvements in the joining of aluminum alloys. Even many studies have been performed; there is still a considerable need to further examine existing and new combinations of process parameters such as tool rotational speed, traverse speed and tool tilt angle. Existing researches are constrained to the microstructure of weld joint. Hence an attempt has been made to explore the optimization of parameters of FSW. Experimental techniques that include statistical design of experiment, such as Taguchi method is considered to achieve an optimal solution. Study on various process parameter of FSW on 6061-T6 aluminum alloy was carried out on vertical milling machine.

5.1 Material Selection

The base material used in this study is aluminum alloy AA6061-T6. The composition and mechanical properties of is given in Tables 1 and 2, respectively.

Table 1 Chemical Compositions of Aluminum Alloy.

Al Alloy	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti
6061-T6	0.4-0.8	0.7	0.15-0.40	0.15	0.8-1.2	0.15-0.35	0.25	0.15

Table 2 Mechanical properties of base metal.

Tensile strength (MPa)	Yield strength (MPa)	% Elongation	Hardness
295	240	8.0	105

Specially designed tool as shown in Fig.1 is used in the Friction stir welding. The material of the tool is HSS M2 Steel Rod of Dia. 22 mm. A non-consumable high-speed steel tool is used for welding 6061 Al alloy having the shoulder diameter of 22 mm and the tool has cylindrical shaped probe (tool pin) with threads. Probe diameter and length is 6 mm and 5.7mm respectively. The diameter of the head is 18mm. The hardness of tool is around 54HRC.

Figure 1 Tool Used For FSW

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5.2 Selection Of Process Parameters And Levels

The main parameters that affect the mechanical properties of FS welded joints and the practical limits are summarized in Table 3.

Table 3—Process parameters values and their three levels

Level	Rotational speed(rpm)	Transverse speed (mm/min.)	Tool tilt angle(deg)
1	500	16	0
2	710	20	1
3	1000	25	2

5.3 Methodology Selection

From the above literature study there was various methodology used to optimize the process parameters by different authors like Taguchi, Response Surface methodology etc. so the Taguchi (L9) orthogonal array is used to optimize the process parameters, such as tool rotational speed, welding speed and tool tilt angle. Analysis of variance was also used to find out the significant parameter that affects the mechanical properties. The following are the steps to be followed for process parameter optimization by this methodology given by Ross and Phillip J. [6-7]:

Step 1: Determine the quality characteristic to be optimized.

Step 2: Identify the noise factors and test conditions.

Step 3: Identify the control factors and their alternative levels.

Step 4: Design the matrix experiment and define the data analysis procedure.

Step 5: Conduct the matrix experiment.

Step 6: Analyze the data and determine optimum levels for control factors.

Step 7: Predict the performance at these levels

A. Selection of Orthogonal Array

As three levels and three factors are taken into consideration, L9 OA is used in this investigation as shown in Table 1. Only the main factor effects are taken into consideration and not the interactions. The degrees of freedom (d.f.) for each factor is 2 (number of levels- 1, i.e. 3 - 1 = 2) and therefore, the total d.f. will be 3× 2 = 6. Generally, the d.f. of the OA should be greater than the total d.f. of the factors. As the d.f. of L9 is 8 it is suitable for the study.

Table-1:-Experimentation control log using OA L9.

Exp.No	RPM	Feed	Tilt Angle
1	1	1	0
2	1	2	1
3	1	3	2
4	2	1	1
5	2	2	2
6	2	3	0
7	3	1	2
8	3	2	0
9	3	3	1

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ISSN (O) 2319 - 8354
ISSN (P) 2319 - 8346

VI. CONCLUSIONS AND FUTURE SCOPE

In this paper, a critical review of different aspects of FSW technique has been illustrated. It has been decided to present the major findings related to FSW at one place so as to provide a clear picture to the reader. Following points can be concluded:

- Friction stir welding owing to its distinctive characteristics: low distortion and shrinkage even in long welds, free of arc, filler metal, and shielding gas, low HAZ, free of spatter and porosity defect is emerging as an alternative to fusion welding. FSW is found suitable for joining similar or dissimilar metals or alloys including aluminum, magnesium, copper, steel, zinc, nickel and its alloys, plastics, etc.
- Like traditional fusion welding butt and lap joint can be carried out in friction stir welding. Although, no special preparation is needed. In addition, it is observed that FSW shows significant enhancement in tensile strength, ductility, fatigue, and facture toughness as compared to fusion welding.
- It is clear that, FSW process parameters: tool rotation rate, traverse speed, tool tilt angle influence the mechanical and metallurgical behaviour of joints and hence, are vital to produce sound and defect-free weld.
- According to available literature, most of the research work is focused on friction stir welding of aluminum, copper and magnesium. Friction stir welding of alloys, plastics, composite materials, etc. is having huge scope for future research.
- The influences of the input process parameters on process performance characteristics and interaction effects are not significantly explored. In-detail study of contribution of the individual input process parameters on process performance characteristics is lacking in literature.
- Mechanism of materials flow, tool geometry design, wearing out of welding tool, and force distribution during welding needs proper attention.

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