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Doe: A Key to Optimize Friction Stir Welding of Dissimilar Aluminum Alloys

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ABSTRACT
The paper deals in emphasizing the importance of DoE in designing the experiments for Friction Stir Welding (FSW) of dissimilar aluminum alloys. DoE provides us series of runs in which purposeful alterations are made to critical process parameters (as input variables) of a system and the effect on response variables is measured. From the available literature, it has been observed that the effect of welding parameters on desired characteristics was determined by taking into consideration one parameter at a time or by using conventional methods like; Single Factor at a Time (SFAT) technique. So without ignoring the limitations of earlier researches, the main focus in this study has been kept on welding of dissimilar alloys (specifically AA-6061 and AA-5086) by using DoE which is quite rarely used Multi-Factor at a Time (MFAT) technique.
***Keywords* -** Aluminium Alloys, Critical to Process parameters, Design of Experiments, Friction Stir Welding.

I. INTRODUCTION

Welding is a process of joining two or more similar or dissimilar materials with the application of heat and with or without application of pressure. Filler materials also may or may not be used. In order to join two or more pieces of metals through any welding process, the most essential requirement is heat. Pressure may also be employed but in many processes, it is not essential. There are two types of welding i.e. Fusion Welding and Solid State Welding. In Fusion Welding, there is no pressure applied but a filler material is always used. In Solid State Welding, pressure is applied along with heat but no filler materials are used.

In recent times, focus has been on developing fast and efficient processes that are environment friendly. The spotlight has been turned on ***Friction Stir Welding (FSW)*** as a joining technology, capable of providing welds that do not have defects normally associated with fusion welding processes [16] [10]. The joining does not involve any use of filler metal and therefore any aluminium alloy can be joined without concern for the compatibility of composition, which is an issue in fusion welding [5]. It has been found as one of the most significant welding process invention from the last two decades. Figure 1 shows Systematic Drawing and Process Principle of Friction Stir Welding.

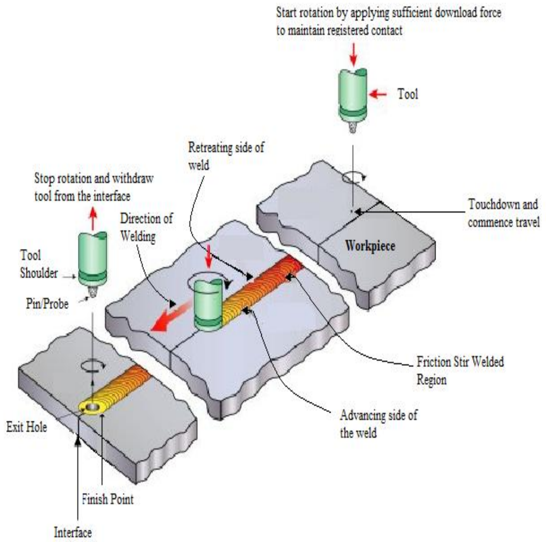

Figure 1: Systematic Drawing and Process Principle of Friction Stir Welding

II. FRICTION STIR WELDING EQUIPMENTS

The major equipments used in FSW are:

2.1 Tool

The tool used in FSW is cylindrical in shape with concave area with a pin which is coaxial with the axis of rotation of the tool. The tool consists of two main parts i.e. a pin or probe and a shoulder. The function of a tool is mixing of the work piece material and heating by frictional hear and hence material selection of the tool is very important factor. The good tool material should feature following properties:

- Good wear resistance.
- High hardness elevated temperatures and should retain the hardness for an extended period.
- Good static and dynamic properties at welded temperature.
- Mechineability and fracture toughness.

2.2 Machine

A conventional Vertical Milling Machine can be used to carry out the FSW process. The machine must have the ability to apply significant pressure onto the workpiece, should offer wide range of tool rotation and feed rate speeds, provides enough space for its working table to holding the welding assembly and rigidly during the welding operation.

2.3 Fixture

The workpieces to be welded have to be securely clamped to prevent the joint phases from being forced apart. Fixture provides the medium in which workpieces are rigidly clamped. Special types of fixtures can be designed as per requirements. Workpieces are clamped on to fixture which is further mounted on the Vertical Milling Machine.

III. PROCESS PARAMETERS IN FSW

Following are some of the critical parameters of FSW which are detailed out in fig. 2.

3.1 Tool Rotation Speed

One of the crucial parameters that have significant impact on the quality of the weld in FSW is Tool Rotation Speed. The speed at which fixed tool rotates in vertical milling machine is referred to as tool rotation speed. Clockwise rotation can be viewed from above the tool, looking down onto the workpiece. Vertical milling machine offers different tool rotation speeds ranging from very low level to quite high levels. Appropriate selection of the tool rotation speed is very much necessary to cause extensive plastic flow of the materials to be welded.

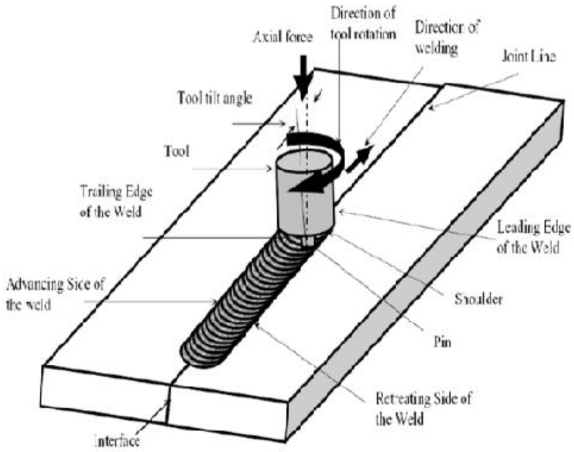

Figure 2: Process parameters in FSW

3.2 Travelling Feed/Feed rate

In vertical milling machine, tool is fixed but only rotates at its position and workpieces that are clamped on to fixture travels. By travelling feed/feed rate, we mean the speed with which workpieces that are clamped onto fixture travels. It may also be termed as welding speed i.e. speed at which welding occurs. The relation between travelling feed/feed rate and the generation of heat during welding is complex but it is generally said that raising the tool rotation speed and reducing the feed rate will result in increasing the temperature at weld surrounding which intern leads to production of successful weld.

3.3 Tool Tip Shape

The shape of the tool is another very important factor that can lead to improvement in both the quality of the weld and maximum possible welding speed. Optimizing tool shape for producing more heat and achieving more efficient stirring offers two main advantages: (i) Improved breaking and mixing of oxide layer. (ii) More efficient heat generation, yielding higher welding speeds and, afcourse, enhanced quality. Different tool tip shapes as used in FSW can be cylindrical, square, triangular, and trapezoidal.

3.4 Tool Tip Plunge Depth

The part of the tool, which paniterates in workpiece during welding is referred to as the probe or tip of the tool. The plunge depth needs to be correctly set, both to ensure that the necessary downward pressure is achieved and to ensure that the tool fully penetrates into the weld region. Plunge depth should be always less than the thickness of the workpiece.

3.5 Tool Tilt Angle

As the tool may in some circumstances be tilted through a small angle, part of the shoulder may be embedded deeper into workpiece. This angle of tilt is referred to as ‘tilt angle’. Tilting the tool by 2-4 degrees, such that rear of the tool is lower than the front, has been found to assist the forging of the material at the heat of the tool.

3.6 Shoulder Diameter

The part of the tool, which is pressed onto the surface of the workpiece during welding is referred to as ‘shoulder’. Tool shoulders are designed to produce heat to surface and subsurface region of the workpiece. So one of the most important parameters of the shoulder is diameter because it has significant impact on the amount of frictional heat generated. Greater shoulder diameter increases the pressure force and the weld shape changes which depreciates the mechanical properties of the welds. So the choice of shoulder diameter requires due consideration.

IV. RELATED WORK

A brief account of literature search on existing research work in FSW carried out by other researchers in India and abroad is presented below.

4.1 Literature related to description and introduction of FSW

A detailed study shows that the readiness level of friction stir welding for aluminum is high with several industrial implementations. Recent advances in pin tool designs and optimized processing parameters have enabled friction stir welding applications in the marine, ground, transportation and automotive industries [1]. A brief review on Friction Stir Welding of aluminum alloys where in Friction Stir Welding process, its importance, various parameters (like traverse speed, rotating speed of motion of tool, axial force and till angles) effecting mechanical and microstructural characteristics has been explained. Main emphasis has been on tool geometry and its implication on mechanical and microstuctural characteristics of the weld [16].

4.2 Literature related to selection of critical to process (CTP) parameters in FSW

The effect of the tool shape on the mechanical properties and microstructures of 5-mm thick welded aluminum plates. The simplest shape (column without threads), the ordinary shape (column with threads) and the triangular prism shape probes were used to weld three types of aluminum alloys. It has been found for 1050-H24 whose deformation resistance is very low, a columnar tool without threads produces weld with the best mechanical properties; for 606l-T6 whose deformation resistance is relatively low, the tool shape does not significantly affect the microstructures and mechanical properties. For 5083-O, whose deformation resistance is relatively high, the weldablity is significantly affected by the rotation speed. For a low rotation speed (600 rpm), the tool shape does not significantly affect the microstructures and mechanical properties of the joints [7].

The work on welding of two dissimilar metal joints AA 6061 and SS 400 and to find optimum operating conditions of Friction Stir Welding is carried out. The parameters considered were tool rotation speed, transverse speed (Feed rate), and tool tilt angle. The impact value was used to evaluate the quality of dissimilar metal bute joints. ANOVA test was used to interpret experimental data [5].

In [11], the mechanical and metallurgical properties of dissimilar joints of aluminum alloy AA 6351-76 and Aa5083-A111 is presented. The technique used was Friction Stir Welding. To weld the joints, different welding speeds were used and then their effects on tensile properties were analyzed. The welding process parameters were -7001 Rotation speed in rpm, welding speed in mm/min and axial force in ton [11].

4.3 Literature related to optimization of FSW

The material flow in butt friction welding by combining traditional metallography as well as X-ray and computer tomography (CT) is elaborated [13]. The two and three-dimensional CT images are used in parallel with micrographs for visualization of the 1ow field. Two procedures for estimating the average velocities for material flowing through the shear layer are studied. The procedures depend on the configuration of marker material relative to the welding direction, i.e. longitudinal and transverse [13].

A detailed study on the effect of processing parameters on mechanical and micro structural properties of AA6056 joints produced by Friction Stir welding is performed [4]. Different samples were obtained by employing rotating speeds of 500, 800 and 1000 rpm and welding speeds of 40, 56 and 80 mm/mm. It was observed that the specimens welded at 56 mm/min showed the best behavior in the low cycle regime.

The author investigated on the mechanical and micro structural properties of dissimilar 2024 and 7075 aluminum sheets joined by friction stir welding. Mechanically properties have been evaluated by means of tensile and fatigue tests. The joints exhibit very good ductile properties after yielding and the UTS is settled at high levels. The specimens fracture surfaces after testing have been deeply analyzed by using a FEGSEM microscope, revealing the defects typology and location after the Friction Stirring process and the microscopic mechanisms occurred during high stress deformations and final failure [3].

In [8], authors used Friction Stir Welding Technique to Aluminum alloy AA-5083 with variation in rotational and transverse speed of tool. During the experimentation, it was found that with increase in transverse speed, heat input generation decreases due to which the cavity or groove like defects were being produced. The Welding parameters considered were rotational speed, transverse speed, plunge depth, tool till initial heating time and tool down speed. The technique of radiography was carried out using digital radiography system.

In [10], authors proposed that with lower welding speed, the weld is perfect and no obvious defects are produced for analyzing defects, technique of radiography was used. With the increase in welding speed, the welding line at bottom is clear and clear flow lines are generated from bottom up to part of weld. Friction Stir welding approach was adopted for welding. As the tool rotation speed increases, the defect rate decreases. The welding parameters that were considered were downward for constant, welding speed constant and rotation speed. Four set of welding trials were made at the base material AA 7075. Tensile test was conducted to determine the tensile properties of weld material, and it was concluded that quality welds could be produced with the tool rotation speeds of 600-1200 RPM [10].

The influence of axial force on the mechanical and metallurgical properties of friction stir welded aluminium alloy AA6082-T651 joints is highlighted [15]. The axial force is varied from 3 kN to 8 kN on the surface of the base material. Tensile test, macrostructure and microstructure tests were performed on all the welded specimens. SEM was used to know the behaviour of the fractured surface of the tensile test specimens. It is found that the joint fabricated at 6 kN axial force has higher tensile strength and good metallurgical properties.

V. GAPS IN EXISTING RESEARCH WORK

The literature found on FSW has not taken into consideration following aspects:

- Most of the work has been conducted on similar alloys like (AA 6061, AA 5083 and AA 2219). Not much work has been done on dissimilar aluminum alloys.
- No significant work has been done on AA 5086 which is indeed very important alloy used in marine engineering and aerospace applications like ship building, fabrication of aircrafts.
- The literature survey indicates that majority of the studies have been conducted by taking into account one parameter/factor at a time (say; tool rotation, tool profile, tool shape, tilt angle etc.). Multi factors at a time have rarely been taken into account. Moreover it is hard to find papers defining impact of two or more factor-combinations or interactions at a time.
- Above literature search indicates that the technique of Design of Experiments (DoE) has not been used in a systematic way and the experiments have been conducted by using hit & trial methods. Prioritization of various CTP parameters is highly lacking.
- The literature surveyed also reveals that wherever DoE has been used, very few had deduced mathematical modeling of process parameters for future scope.

VI. PROBLEM FORMULATION

Without neglecting the limitations of the earlier researches, the main focus in this research has been kept on welding of dissimilar alloys, specifically, AA 6061 and AA 5086. These are two dissimilar aluminium alloys that are widely used in aerospace, ship building and other fabrication industries as these aluminium alloys have high corrosion resistance properties and offers high strength-to-weight ratio. As till now, the design of experiments using multiple parameters was primarily done using traditional approaches. So, in this work, Minitab 16 release software will be used to generate an orthographic matrix of designed experiments. The tool will not only be used to carry out the statistical analysis of experimentation and to generate graphical implications of achieved results but also it will be utilized to optimize the selected process parameters effectively.

Therefore keeping in view the background, literature review and gaps thereon, this research work aims at:

- Selection and prioritization of various Critical to Process (CTP) parameters.
- Identification of key characteristics (Desired Mechanical properties).
- Mathematical Modeling (equation formulation for various key characteristics).
- Optimization through DoE (by using Minitab 16 release version).
- Scope of present work in future.

VII. PROPOSED METHODOLOGY

Keeping in line with the objectives detailed in the Section VI, a step by step methodology of conducting the research work is given in figure 3.

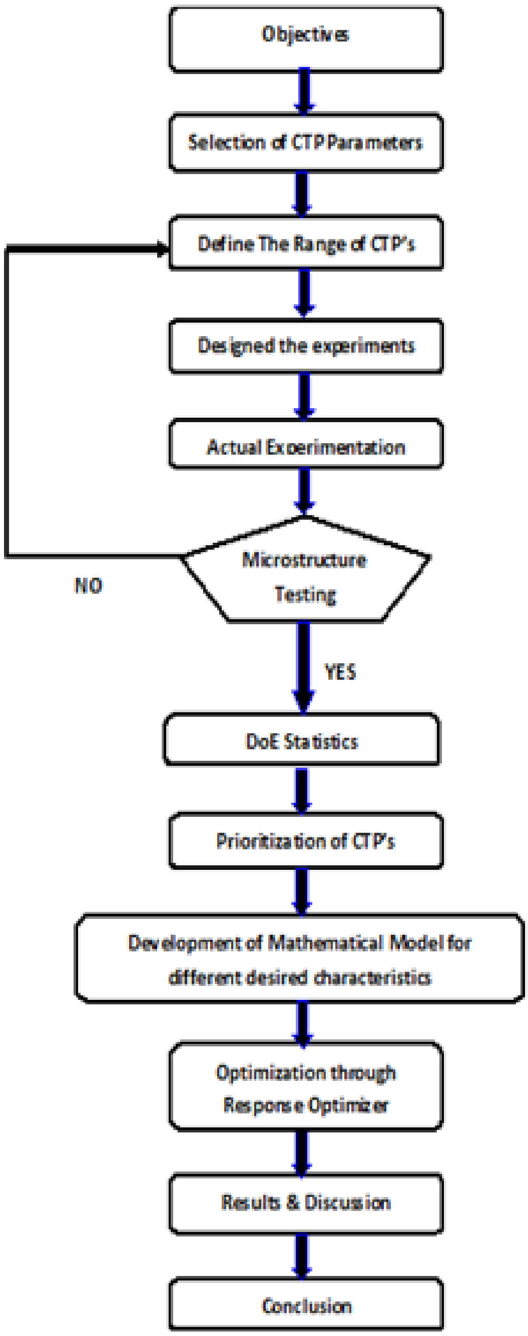

Figure 3: Flow Chart representing methodology that will be adopted to carry out research work.

VIII. CONCLUSION

Majority of the research studies on FSW as per literature review has been done by taking into account one factor at a time (OFAT).(i.e. Tool rotation speed, tool profile, tool tilt angle, welding speed etc.) Multi factors at a time have rarely been taken into account. Traditional methods of conducting mechanical experiments involves hit and trial methodology taking into consideration one factor at a time. The limitations of the traditional methods of designing experiments are overcome by the help of using DoE. These advantages includes assessing the impact of multi factors and their interactions to find out the effect on response variables; determining statistically significant factors which makes optimization process more accurate and presenting the graphical implications of different factors effecting response variables.

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