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# Finite Element Modelling (FEM) of Friction Stir Welding (FSW) process for optimal process parameters of AA2024-T3 and AA6061-T6 using ABAQUS

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**ABSTRACT:** Friction stir welding (FSW) is a modernization of the traditional friction welding. It is a process that was created by The Welding Institute in Cambridge, England in 1991. It is a mechanical cycle where by solid-state welding is performed utilizing heat created from the friction of a pivoting instrument and plastic distortion of weld material. Two materials that are to be welded together are held up against a support plate utilizing a clamping framework. The rotating tool is then gradually diving with a downward force into the weld joint. It stays for a couple of moments while enough heat is produced because of friction that the welded material would start to stream around the device. When that moment is reached, the tool shall be crossed along the joint making the weld behind the tool as it moves along. The primary advantage of friction stir welding is that the pieces to be welded would not be arriving at their meltingpoints.

**KEYWORDS:** Friction Stir Welding, Finite Element Modelling, ABAQUS, AA2024-T3, AA6061-T6.

## I. INTRODUCTION

Friction stir welding (FSW) was invented at The Welding Institute (TWI) of the United Kingdom (Cambridge) in 1991 as a solid-state joining technique, occurring below the solidus temperature of the metals being joined and was initially applied to aluminum alloys. It is being touted as the most significant development in metal joining in the last decade. The Figure 1.1 shows the schematic representation of friction stir welding process (Kumar et al., 2009).

### A. Process Phases.

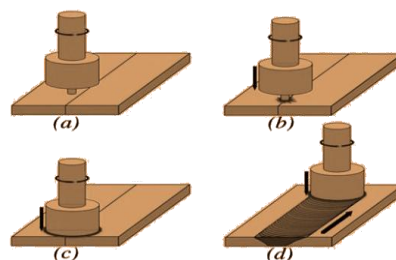


Figure 1. Schematic representation of FSW process; a) Rotating tool before plunging, b) Plunging stage, c) Tool shoulder touches the work piece surface producing frictional heat, d) Rotating tool traverses along the work piece.

A schematic of FSW process is shown in Figure 1.1 above. The work piece is placed on a backing plate and is clamped rigidly to the fixture to eliminate any degrees of freedom. Heat is produced due to shoulder surface friction with the top surface of the work piece, which softens the material to be welded. The tool shoulder is the primary means of generating heat during the process. It prevents expulsion of the material and guides the movement of the material during welding. The tool pin is normally 1/3rd the diameter of the shoulder extending from the shoulder and rotates with a high speed of 1000's of rpm. It is slowly plunged into the work piece until the shoulder surface touches the work piece. The pin then moves along the area to be welded on the work piece with a specified travel rate. Tool pin is the

secondary means of heat generation. The pin of the rotating tool provides the stirring action to the materials of the two plates to be joined. As the tool travels along the path of interest, the weld cools, thereby joining the two plates together.

## II. RELATED WORK

Since its invention in 1991, FSW has been an active research area. Considerable numerical work on FSW has been accounted in various published literature, which are focused on residual stress, heat transfer and material flow aspects. Several approaches have been utilized to recreate the FSW process. The typical approach for FSW modelling is to obtain numerical predictions and then compare and validate the results against experimental work.

### A. Analysis Methods.

An engineering problem can be simplified by breaking it into following forms of analysis i.e. static, dynamic, heat transfer and a variety of coupled problems. Analysis can be performed using Implicit, Explicit or either CFD solvers based on the problem to be solved and intended results. The selection of suitable module and formulation used in model plays a vital role in correlation of simulation results to that of experimental results.

### B. Formulations.

Formulations in context of FSW mean the equations/components are in appropriate relationships or structures, according to a formula which governs the simulating process. The following sections reflect the framework described in the open literature and discuss some of the advantages and disadvantages of various formulations in the context of FSW application.

- a. Eulerian or CFD approach.
- b. Lagrangian approach.
- c. Arbitrary Lagrangian Eulerian (ALE) approach.
- d. Coupled Eulerian-Lagrangian (CEL) approach.

#### a. Eulerian or CFD approach.

Obtains information on material flow, but neglects free surface deformation and effect of deformation history.

#### b. Lagrangian approach.

Simulates material flow, including heat from friction and material deformation, but requires complex remeshing.

#### c. Arbitrary Lagrangian Eulerian (ALE) approach.

Can simulate flow and include heat from friction and deformation; avoids degeneration of mesh; allows for deformation of free surface.

#### d. Coupled Eulerian-Lagrangian (CEL) approach.

With capabilities apart from ALE, it can accurately predict the presence of defects and takes less simulation time.

### C. Conclusion from Literature review.

Ample research has been done on experimental and numerical investigation of FSW. Temperature, Material flow, Microstructure and Residual stress predictions were done using FE Modelling Packages and were validated experimentally, but all the four factors were not analyzed in a single FE Model. To obtain defect free weld with better properties, it is necessary to optimize input process parameters. The incredible favourable position of CEL approach is that all issues related with mesh bending are wiped out as the Eulerian depiction permits finite elements to be fixed in space and the material to move through these components. This reality empowers application in mathematical stimulation of issues including extraordinary material disfigurement as it happens during FSW. Optimal process parameters were obtained using various Design of Experiment techniques and there are no attempts made to find optimal process parameters using FE Modelling. Hence, there is an ample scope for research in this aspect. In view of the above, it is proposed to take up detailed study on three-dimensional (3-D) FE modelling of FSW process using the most widely used FEM software ABAQUS. This would help in obtaining the optimal process parameters for FSW process. algorithm.

### III. METHODOLOGY

To accomplish the research objectives set forth for this study, a methodology was developed. The methodology is essentially a model-based approach for optimization of FSW process.

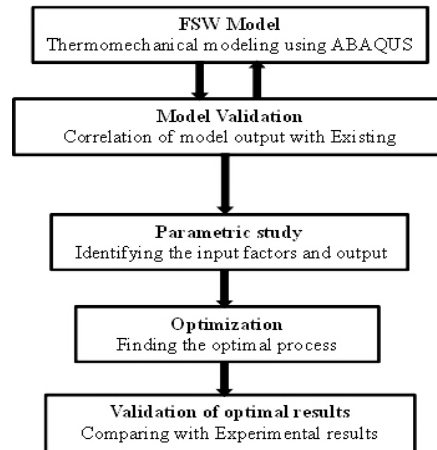


Figure 2. Methodology of model-based optimization of FSW process

The first thing was to develop and validate a thermo-mechanical model of FSW process in consideration of various published papers as discussed in literature review. The thermo-mechanical model was developed using commercial FEA program ABAQUS-6.12. In order to validate the developed model, the output of the model was correlated with the published results. Once developed, the thermo-mechanical model was used to simulate the process. The model was then extrapolated to perform parametric examinations so as to research impacts of different process boundaries on temperature dispersion and residual stress in the workpiece. In the following stage, constrained optimization models were planned with objective of expanding throughput and limiting assembling costs. Finally, the optimal results are validated by Comparing with Experimental results.

### IV. NUMERICAL AND EXPERIMENTAL DETAILS

Numerical methods offer many advantages over analytical methods, being better suited to finite plate geometries, temperature-dependent thermal properties, and complex boundary conditions. The tool and backing plate can also be explicitly included as conducting solids in the thermal analysis. summarizes the ingredients required for a numerical solution of the thermal field: the heat input, material thermal properties, and thermal boundary conditions.

#### A. Finite Element Modelling.

In the analysis of FSW using FE simulations, predictions (required results) are greatly influenced by two major factors; Flow stress characteristics of work materials to be welded. Friction characteristics (Contact condition) mainly at the tool-work interface. In this study, a Coupled Eulerian Lagrangian finite element formulation is used to simulate FSW of 2024-T3 aluminium alloy. The effects of using various tool-work interface friction models on the simulations are investigated. Also, the effects of material constants of material models are discussed. Flow models should be able to simultaneously capture the thermal and mechanical aspects of a given problem in adequate detail to address the following topics. Flow visualization, including the flow of similar /dissimilar metals. Hence the Johnson–Cook model with variation in constants for aluminium alloy 2024-T3 is analysed here for accurate results and with the flow stress data drawn from the hot working guide.

Table 1. Material constants for Johnson-cook

Material constants for Johnson-cook						
A (MPa)	B (MPa)	n	C	m	T <sub>melt</sub> (°C)	T <sub>ref</sub>
369	684	0.73	0.0083	1.7	502	25

A variety of friction coefficient values have been found in literature with the majority of them being a constant value. Tutunchilar et al. (2012b), used friction coefficient of 0.4, 0.5, and 0.6, under 100 mm/min transverse speed and 900

rpm rotational speed. It was found that using hybrid model and friction coefficient of 0.7 gave best results in view of temperatures. Also according to investigations from Kumar et al. (2009), the coefficient of friction and temperatures do have a synergic influence on each other and found that the coefficient of friction in the FSW condition was as high as 1.2 to 1.4 at 4000C to 4500C.

Table 2. Material properties of AA2024-T3

Material properties	Value
Young’s modulus of elastic. [GPa]	73.1
Poisson’s ratio	0.33
Initial yield stress [MPa]	345
Ultimate tensile strength [MPa]	483
Thermal conductivity [ $Wm^{-1}K^{-1}$ ]	121
Coefficient of thermal expansion [ $^{\circ}C^{-1}$ ]	$24.7 \times 10^{-6}$
Density [ $kgm^{-3}$ ]	2770
Specific heat capacity [ $Jk^{-1}g^{\circ}C^{-1}$ ]	875
Solidus [ $^{\circ}C$ ]	502
Liquidus [ $^{\circ}C$ ]	638

Therefore, simulations were performed by varying the friction coefficient values from 0.1 to 2 to see the effect on results by each individual value.

B. Tool Geometry and Work-piece

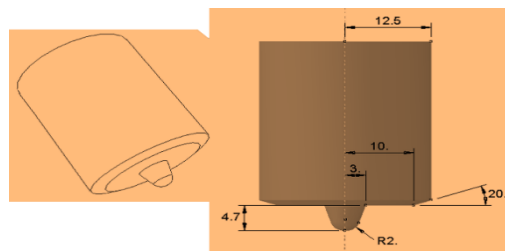


Figure 3. Geometry of tool employed

C. Experimental Details

The experimentation is carried out to validate the numerical solutions. However, it is planned to carry out experimentation only for the optimum configuration to verify the values obtained from the numerical solutions.

a. Experimental Setup and Standard Features

Figure 4.4 shows the BiSS 5 Axis friction stir welder. The standard features of BiSS 5 Axis friction stir welder are as follows;

- 5 axes simultaneous control
- Specimen mounting area 500mm x 500mm
- Suitable to weld steel, titanium, aluminium alloys and mix of thickness from 0.5mm to 65mm
- Vertical load capacity is 50kN with max. 3000rpm at constant torque
- 500mm stroke length in X and Y axis.

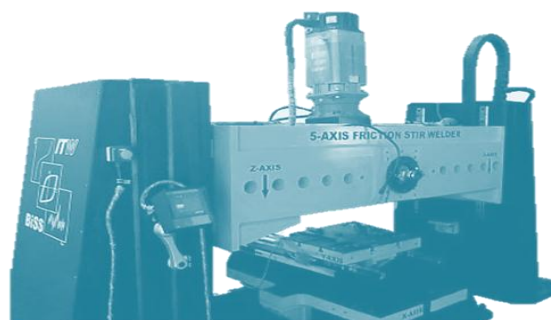


Figure 4. BiSS 5 Axis friction stir welder.

b. Steps in Conducting the Experiment

- Step 1

The step 1 is achieved by selecting AA2024-T3 material and the material is cut to the required dimension by using suitable cutting machine.

- Step 2

The step 2 is achieved by marking the material using suitable marking tool. Suitable holes are drilled to a calculated depth of 4mm using vertical drilling machine. The thermocouples are then placed in the holes. The thermocouples are used to record the temperature readings.

- Step 3

The step 3 is achieved by selecting a range of welding speed & tool rotation respectively. Here an attempt is made to take both the extremes i.e. upper and lower limit.

- Step 4

The welded material is cut into suitable dimension using suitable cutting machine. The cut material is then polished using grit grinding machine, emery paper, silicon carbide polishing and diamond polishing. The polished material is then etched using suitable etchant. The etched material is then placed under microscope and the microstructure is obtained.

## V. RESULTS AND DISCUSSIONS

### A. Effect of Coefficient of Friction

The Figure 5 shows the effect of coefficient of friction on void size at rotational speed of 1000 rpm.

The simulation results show that the coefficient of friction has a major effect on void formation, the lower the friction coefficient is applied, larger the void is formed.

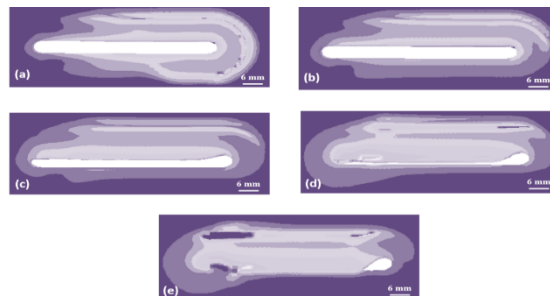


Figure 5. Effect of coefficient of friction on void size (Top view); (a) At = 0.2, (b) At = 0.4, (c) At = 0.6, (d) At = 0.8, (e) At = 1

As the friction between tool and the workpiece increased the formation of void and moment of material was closer to that of experimental conditions. It can be seen that any value of  $\mu$  resulted in unrealistic prediction of results. Also considering  $\mu = 1$  lead to over softening of material, which intern showed the defect as shown in Figure 6.

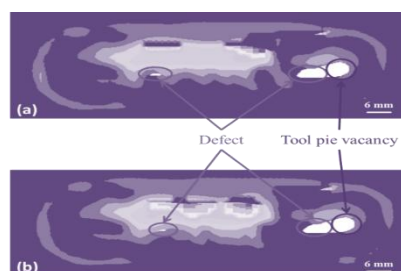


Figure 6. Effect of high coefficient of friction (Top view); (a) At = 1.4, (b) At = 1.6

In Figure 5.2 the percentage of error is calculated by considering the maximum temperature of 404.360C, recorded by thermocouple during the experiment. The resulted simulation temperature at  $\mu = 1$  is in close agreement with

thermocouple reading with 6.46% error, which is unacceptable range. The error could be because of considering constant coefficient of friction throughout the simulation.

B. Optimizing the Process Parameters.

Optimization is an iterative process of finding the optimal parameters without violating the set constraints. Friction stir welding process operation in general can also be optimized by obtaining optimal values for parameters such as tool rotational speed, axial force, traverse speed, tool dimension, temperature, stress, strain, strain rate, defects and other such parameters. Several optimization techniques could be applied to optimize FSW models.

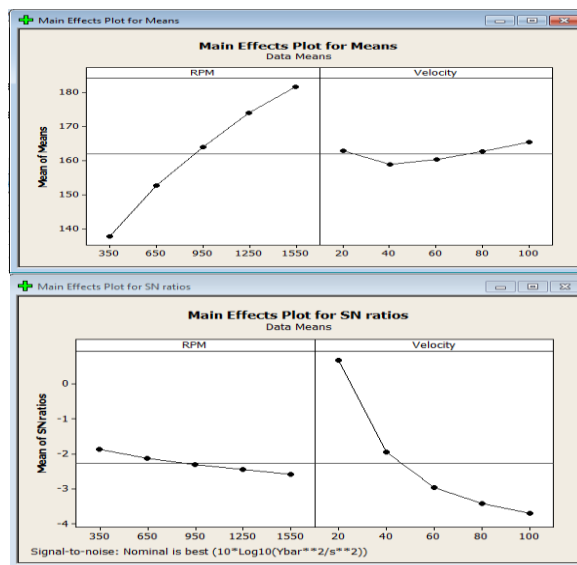


Figure 7. Main Effect Plot for means and Main effect plots for S/N ratios

However, as the FSW is relatively new technology, there have been only a few attempts to use mathematical optimization techniques to optimize the process. Here a basic level of optimization is done to show the capability of the results obtained from FE model for application in optimization. With the data from the simulated model a Taguchi and Response surface optimization techniques were carried out using MINITAB. The optimization process is based on defects observed, welding time taken and temperature range, with tool rotation and weld velocity as variables.

Here with the results of Taguchi and Response surface optimization techniques obtained from MINITAB, optimized process parameter predicted were 950 rpm with 60 mm/min. At 950 rpm with 60 mm/min the experimental results were also correlating with that of simulation results. This show in a border sense the capability of results obtained from FE model in performing optimization.

## VI. CONCLUSION

Based on the current investigation and the results obtained, following observations were made:

- The proposed FE Modeling method exhibits the potential of defect prediction for given process conditions which ultimately help in selecting the appropriate process parameters.
- CEL method helps in reducing simulation time to a larger extent thereby making FE simulations of FSW and its variants time efficient.
- The proposed method presents the strong possibility of widening the effective optimization study on FSW and its variants.
- The proposed method helps in the right selection of tools in order to get the desired weld nugget morphology and working temperature with minimum possible power consumption.

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