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NUMERICAL SIMULATION ON THE EFFECT OF TOOL SHOULDER END FEATURES ON DEFORMATION CONDITIONS USING MICRO-FSW OF AA 6061-T6

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ABSTRACT

Micro friction stir welding (μFSW) is the friction stir welding process (FSW) with the thickness of the workpiece being welded is 1000μm or less. The process is beneficial because of no fluxes and shielding gases and can find applications in thin-walled structures, electrical, electronic, and micro-mechanical assemblies. μFSW is a solid-state process so, there is no solidification segregation and reduced inter-metallic formation, which can affect mechanical and electrical performance and lifetime. Friction stir welds can show grain refinement and even improved material properties. This work implemented the thermomechanical model of micro friction stir welding process using ABAQUS to investigate the effect of featured and featureless tools on temperature distribution, plastic strain and average stress. Aluminum alloy 6061-T6 0.5mm sheet and H13 Steel are used as workpiece and tool material respectively. Based on the simulation results, we found that: (1) The micro featured tool shoulder is producing lower welding temperatures during the process. (2) Plastic Strain, in the case of the featureless tool, is higher during plunging, and it is lower during tool travel. (3) In both cases, higher Stress is observed at the front of the tool.

Keywords: Thermomechanical, FSW, ABAQUS, TOOL DESIGN, Simulation Analysis

I. INTRODUCTION

Friction stir welding (FSW) was invented at the Welding Institute (TWI) of the UK in 1991 as a solid-state joining technique and was initially applied to aluminum alloys [1][2]. Fig 1.1 shows the process schematically.

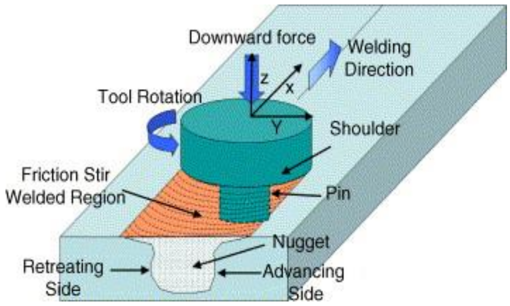

Fig 1.1 shows the schematic of FSW

FSW has been used in high technology applications such as aerospace to automotive until high precision applications such as micro-welding. In FSW, a non-consumable rotating tool with a specially designed pin and shoulder is inserted into the abutting edges of sheets or plates to be joined and subsequently traversed along the joint line[3]. In FSW, metals are joined in the solid-state due to the heat generated by the friction and flow of metal by a pinned tool's stirring action. The frictionally heated material around the tool pin is plastically deformed and extruded to the pin's back, where it forms the weld. The majority of the heat generated from the friction, i.e., about 95%, is transferred into the workpiece, and only 5% flows into the tool [4]. The solid-state nature of the FSW process results in a highly characteristic microstructure. The microstructure can be broken up into four zones as weld nugget (dynamically recrystallized zone or stir zone), thermo-mechanically affected zone (significant plastic strains without recrystallization), heat affected zone (a region subjected to thermal cycle with no plastic deformation), and unaffected material or parent metal (material remote from the weld which isn't affected by the thermal cycle of weld). The heat generation rate, temperature profile, and the load distribution within the workpiece are strongly dependent on process parameters entail the axial force for plunging, rotational speed, welding speed, tilt angle, and tool geometry. FSW is a novel green manufacturing technique due to its energy efficiency and environmental friendliness. The maximum temperature created by the FSW process ranges from 80 to 90% of the melting temperature of the material being welded. FSW offers several advantages over the conventional fusion welding process due to its low heat input and absence of melting and solidification process.

1.1 Advantages of FSW

Metallurgical advantages: -

Since FSW is a Solid-state joining process. Grain refinement process takes place, and fine equiaxed grain is obtained. FSW avoids many of the defects associated with melting and solidification during fusion welding's, such as pores and solidification cracks. No loss of alloying elements is observed. It can join many 'non-weldable' aluminum alloys, namely from the 2xxx and 7xxx series.

Mechanical advantages: -

Low distortion.

Residual stress is low.

Good dimensional stability and repeatability.

Environmental benefits: -

Expensive consumable materials such as filler, fluxes, and a shielding gas are not required. No surface cleaning is required. Eliminate grinding wastes and no harmful emissions.

1.2 Zones of the FSW process

FSW weld showing four distinct zones as shown in figure 1.2;

Un-affected material: The material, with no deformation and having similar microstructure or mechanical properties as of base, remote from the weld.

Heat affected zone (HAZ): The material nearer to the weld and experience a thermal cycle with modified microstructure or mechanical properties with no plastic deformation.

Thermo-mechanically affected zone (TMAZ): In this region, the FSW tool has plastically deformed the material, and the heat from the process will also have exerted some influence on the mate rial, and there is generally a distinct boundary between the recrystallized zone (weld nugget) and the deformed zones of the TMAZ.

Weld Nugget or Stir Zone: In the central region of the weld, which is a fully recrystallized area and this region occupies fine equiaxed grains and, sometimes, called the stir zone, refers to the zone previously occupied by the tool pin.

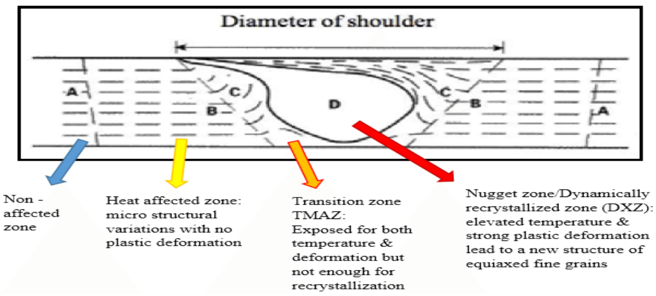

Fig. 1.2 Schematic cross-section of a typical FSW weld showing four distinct zones: (A) unaffected material, (B) heat-affected, (C) thermos-mechanically affected, and (D) stir/nugget zone [5].

1.3 Basic forces applied in FSW

1. Downward force, which is significant large force required to:
- Ensure constant contact of the shoulder with workpiece
- Maintain correct penetration of the probe
- Provide load for generation of friction at shoulder-workpiece interface
2. Rotational force (torque on the tool), which:
- Produces friction between tool probe and weld
3. material and internal friction in the weld
- Produces friction at the shoulder
- Transports weld material around the tool

4. Transverse force, which:
- Traverse the tool along the weld line
- Combines with other forces to transport the weld material

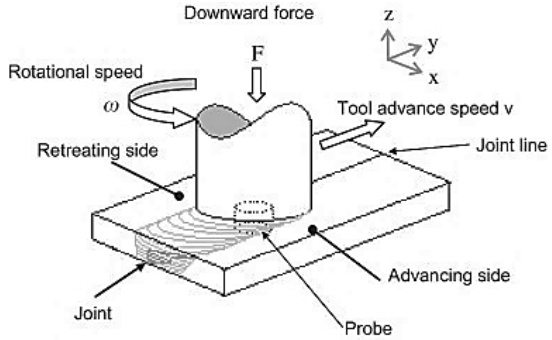

Fig 1.3 Shows basic forces during FSW process

1.4 Heat generation Equation

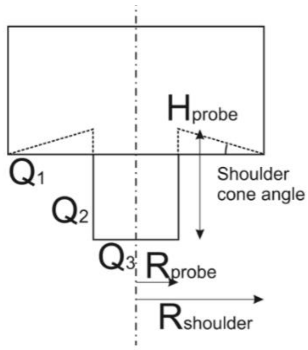

Fig 1.4 Shows Heat generated at different surfaces of the tool

Q1- Heat generated at tool shoulder

Q2- Heat generated at vertical surface of pin

Q3- Heat generated at tool tip

Heat generated per unit time

dQ = W*r*dF

The three contributions are combined to get the total heat generation estimate Q_{total}

$$Q_{\text{total}} = Q_1 + Q_2 + Q_3 = \tfrac{2}{3}\pi\tau_{\text{contact}}\,\omega\left((R^3_{\text{shoulder}} - R^3_{\text{probe}})(1+\tan\alpha) + R^3_{\text{probe}} + 3R^2_{\text{probe}}H_{\text{probe}}\right)$$

In the case of a flat shoulder, the heat generation expression simplifies to

$$Q_{\text{total}} = \tfrac{2}{3}\pi\tau_{\text{contact}}\,\omega\left(R^3_{\text{shoulder}} + 3R^2_{\text{probe}}H_{\text{probe}}\right)$$

II. METHODOLOGY

A methodology was developed to accomplish the research objectives for this study. The methodology was essentially a model-based approach for the optimization of the FSW process. Based on the literature survey, the material is being selected, and then the foremost study is done for the tool shoulder geometries. The obtained tool is being modeled using CREO. The next task was to develop a thermomechanical model of the FSW process in consideration of various published papers, as discussed in the literature review. The thermomechanical model was developed using a commercial finite element analysis program ABAQUS. Once developed, the thermomechanical model was used to simulate the process. The model is being used to study the output response for the input parameters while keeping th e various constraints associated with the process. The obtained parameters are optimized, keeping in mind the defect-free joint and standard mechanical properties.

Optimized results of the featureless and featured tool are compared against each other for the justification of the current work. The overall methodology is shown as a figure

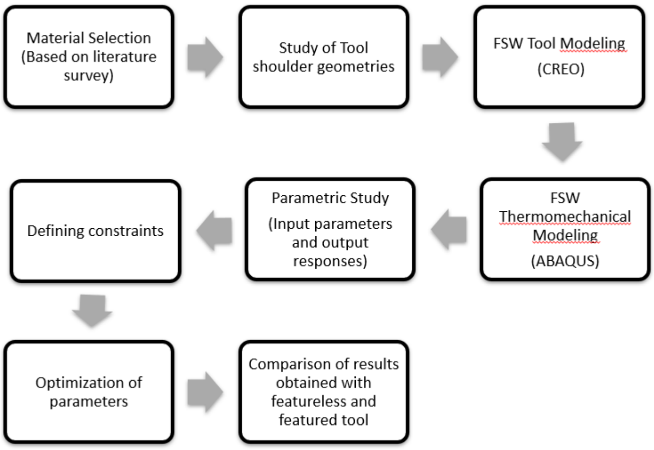

Fig 2.1 Shows the flow chart of methodology used in this work

2.1 Specifications

Workpiece:

0.5mm thick sheet of Aluminum Alloy (AA6061-T6) is used as workpiece for the simulation of micro friction stir welding using ABAQUS. The composition of workpiece material is given in table below

Element	Al	Si	Mg	Cr	Cu
Percent%	97.9	0.6	0.1	0.2	0.28

Tool:

H13 Steel is used as tool material for featured and featureless tools. Diameter of the tools is selected as 6mm based on the literature survey. Topology optimization begins with an initial design considering the resemblance of the actual components. After carrying out a literature survey, we come to the following design of the featured tool associated with our work. The tool considered for simulation of all the welds is a pinless tool with dimension 6 mm as shoulder diameter and height as 2 mm. Specific to the micro-featured tool, the cross-section used for spiral micro-features is circular, with 0.12 mm depth and 0.3 mm width. CREO model of the featured tool and assembly of tool and workpiece in ABAQUS can be seen in pictures below.

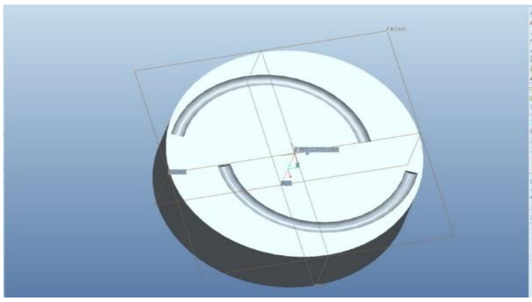

Fig 2.2 CAD model of the micro-featured tool developed using software CREO

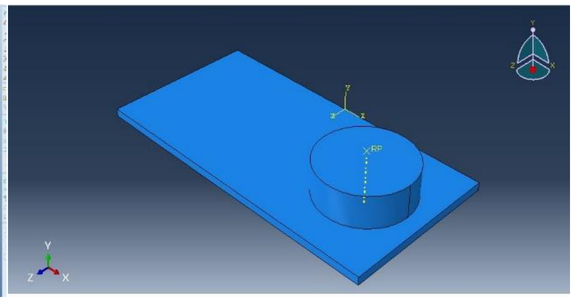

Fig 2.3 Assembly of the tool and workpiece

III. MODELING AND ANALYSIS

3.1 Numerical simulation

The Finite Element Method (FEM) offers a way to solve complex continuum problems by subdividing it into a series of simple interrelated problems. FEM is most commonly used in numerical analysis for obtaining approximate solutions to a wide variety of engineering problems.

The commercially available ABAQUS explicit finite element software is used to model and analyze the process steps that involve plunging and traversing stages. Coupled-Eulerian Lagrangian (CEL) technique is used for simulation because by using this the exceesive mesh distortion problem can be overcome. In order to get temperature profile, average stress, and distortion from the welding process, thermomechanical models are developed with some assumptions.[6]

The following assumptions are made in developing the model:

- The heat generation is due to friction only.
- The heat generated during penetration and extraction is not considered.
- The coefficient of friction is considered as constant.
- Material properties are uniform.
- Material is isotropic and homogeneous.
- No melting occurs during the welding process.
- Heat transfer by radiation is negligible.

The important process characteristics which are required to be considered for the purpose of modeling are as follows:

- Moving heat source;
- Weld speed;
- Axial load and
- Material properties

3.2 Mesh Sensitivity Analysis

Mesh sensitivity analysis is essential to check the variation in results with respect to change in element size. The model should be insensitive to the changes related to the element size or the number of elements. With different combinations of the element sizes, the variation in the results is checked and found acceptable. For the meshing, the workpiece element shape is considered as a hexahedral with an Eulerian approach to avoid excessive distortion. The element type considered here is of EC3D8RT type with a total number of 10000 elements. Linear geometric order with minimum element size 0.2 mm is used while working with two different tools, featureless and featured.

Tool (featureless)

- Element shape is tetrahedral.
- The element type is C3D10MT.
- Geometric order is quadratic .
- Total number of elements 906360.
- The minimum element size is 0.06 mm.
- The tool is considered as lagrangian body.

Tool (featured)

- Element shape is tetrahedral.
- The element type is C3D10MT.
- Geometric order is quadratic.
- Total number of the element 906669 (Increase in total no. of elements is due to the presence of extra surfaces as grooves)
- The minimum element size is 0.06 mm.
- The tool is considered as lagrangian body.

3.3 Boundary Conditions

In the present work, sequentially coupled finite element analysis is carried out. The temperature values obtained from the thermal analysis are applied as body loads in the mechanical analysis. The contact in the model has been formulated using penalty method. Where the tool is treated as a rigid Lagrangian body, and the workpiece is assigned with Eulerian elements. The penalty method is employed to calculate the interaction force between the Lagrangian body and Eulerian elements. The following boundary conditions are utilized for mechanical analysis:

- The workpiece is fixed in all directions, i.e., displacement in all directions is zero.
- There are no displacements along the symmetric surface.

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- Tool rotation speed is 2000 rpm, and the tool travel speed is 300 mm/min.
- The temperature surrounding the whole model was set to the environmental temperature of 20° C at the beginning of the analysis.
- The coefficient of friction is taken as 0.4 using the penalty method.
- 100% conversion of friction into heat is considered.

IV. RESULTS AND DISCUSSION

In this study, ABAQUS software is selected to simulate plunging and traverse steps in the friction stir welding process. The software has the function of effective mesh re-division and has a unique point tracking method, which provides information on temperature, average stress, and plastic strain at every point.

4.1 Temperature Distribution

The present model results were accomplished by comparing the temperature values obtained with featured and featureless tools using Finite Element simulation. The simulation results demonstrate that when the tool comes into contact with the AA 6061 T6 plate to start penetration, the temperature has risen to some maximum value in the zone locally beneath the tool bottom surface, and semicircle temperature contours propagate through the plate surface. The temperature keeps growing up at the same site until the shoulder comes in contact with the AA 6061 T6 plate; subsequently, the maximum temperature point skips to the corner zone. During tool travel, the contact between tool and workpiece increased, causing the temperature to grow up to its maximum value (652°C with the featured tool and 666°C with featureless tool) around the shoulder-workpiece interface; this is due to the occurrence of complete contact between the workpiece and the tool.

Fig 4.1 and 4.2 Show the temperature distribution at the end of plunging operation with featured and featureless tools, respectively, where micro featured tool shoulder is producing lower welding temperature because of the effective contact surface area for frictional heat generation decreases compared to the featureless flat tool shoulder. Also, in the featured tool, the heat could be carried away with the material flowing into micro-features of the tool.

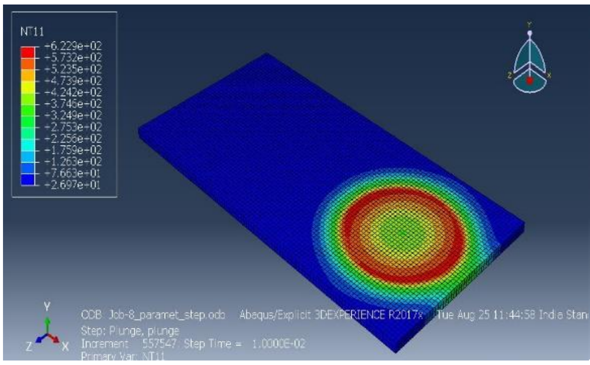

Fig 4.1 Temperature distribution at the end of plunging operation with the featured tool.

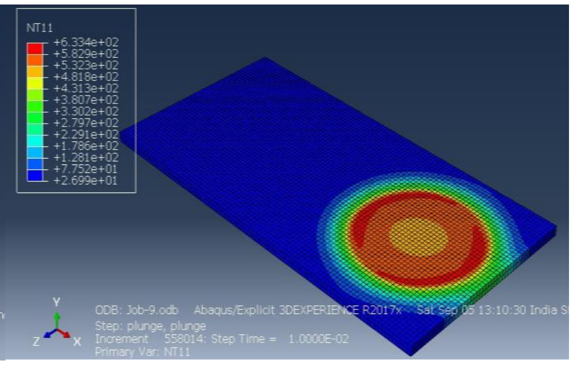

Fig 4.2 Temperature distribution at the end of plunging operation with the featureless tool.

Fig. 4.3 and 4.4 show the temperature distribution at the end of tool travel with featured and featureless tools, respectively. Temperature changes across the plate width because heat is being conducted.

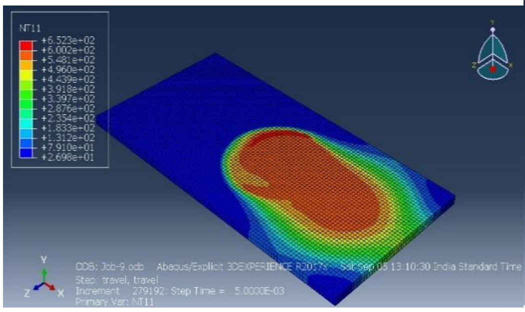

Fig 4.3 Temperature distribution at the end of tool travel with the featured tool

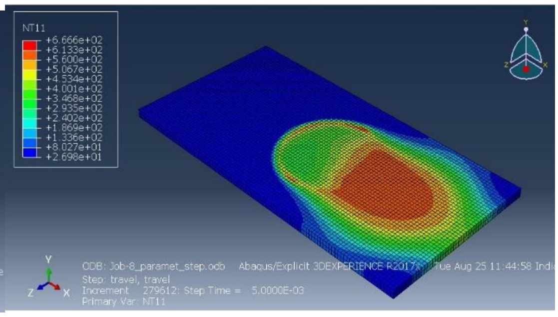

Fig. 4.4 Temperature distribution at the end of tool travel with featureless tool

4.2 Plastic Strain

Plastic strain plays an essential role in investigating the microstructure, grain size, and material deformation. The current study investigates plastic strain quantity. The variation of the equivalent plastic strain at the end of the plunge is shown in Figures 4.5 and 4.6 for featured and featureless tools, respectively. At the beginning of the plunging operation, the plastic strain is higher in the case of featureless tool shoulder because of complete contact between workpiece and tool. Whereas, for the featured tool, the value of plastic strain is lower (less contact area between workpiece and tool). For both cases, the value of plastic strain at the periphery of the tool is higher than that of the center of the tool because velocity is a function of radius

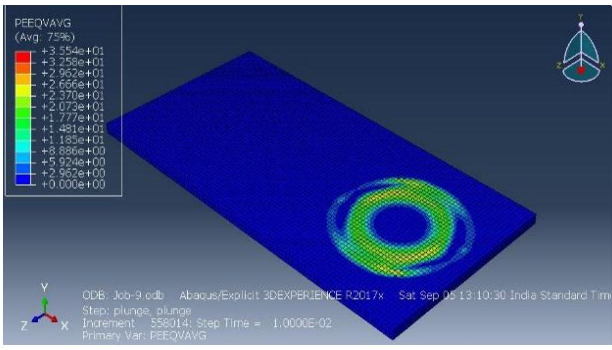

Fig. 4.5 Plastic Strain at the end of plunging operation with the featured tool

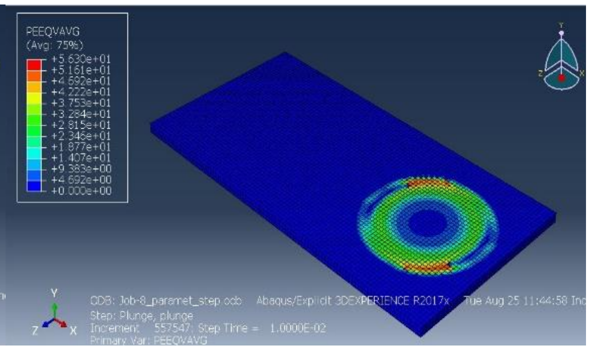

Fig. 4.6 Plastic Strain at the end of the plunging operation with the featureless tool

Fig. 4.7 and 4.8 Show the Plastic Strain along the welding direction of featured and featureless tools, respectively. Plastic strain, in the case of the featured tool during the tool travel, is low because material build-up happens on the tool surface due to localized heat.

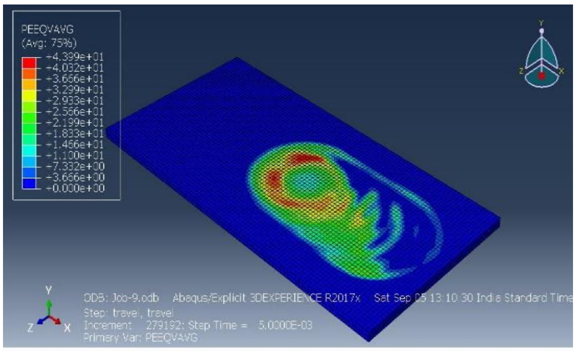

Fig. 4.7 Plastic Strain at the end of tool travel with featured tool

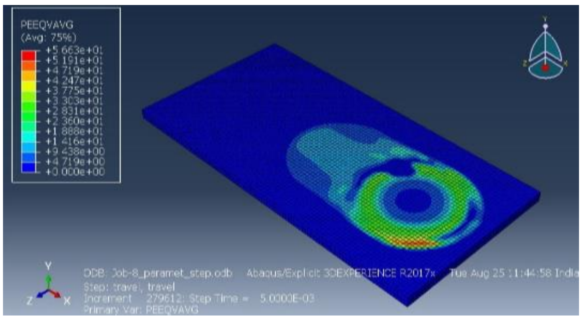

Fig. 4.8 Plastic Strain at the end of tool travel with the featureless tool

4.3 Average Stress

In the current study, stress is computed as a volume fraction weighted average of all materials present in the element. The use of volume fraction averaged Stress (SVAVG) in simulation substantially decreases the size of the output database for models with eulerian materials. The variation of the stress value throughout the entire process time indicates that workpiece temperature performs a significant function in controlling the stress

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magnitude and, consequently, in the building of a flawless weld. Fig 4.9 and 4.10 show the average stress at the end of the plunging operation with featured and featureless tools, respectively. The value of stress is low, where the temperature is high.

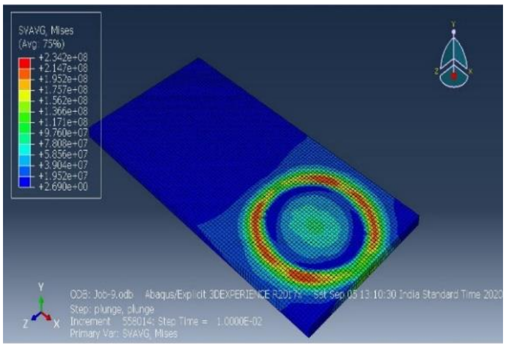

Fig. 4.9 Average Stress at the end of plunging operation with featured tool

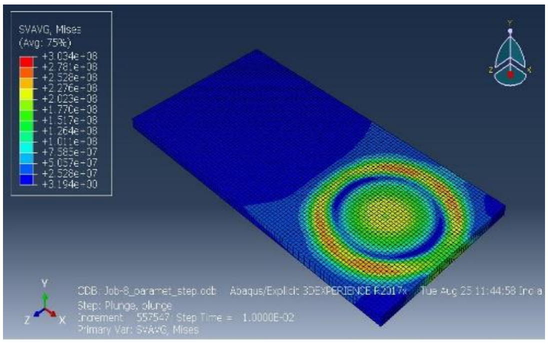

Fig. 4.10 Average stress at the end of plunging operation with the featureless tool

Fig. 4.11 and 4.12 Show average stress at the end of tool travel with featured and featureless tools, respectively. In both cases, higher stress is observed at the front of the tool, because it is facing the solid material. This stress on the front of the tool can be reduced by providing tool tilt.

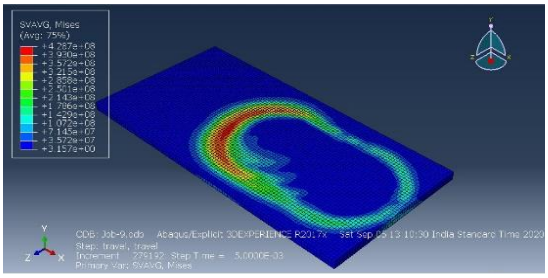

Fig. 4.11 Average Stress at the end of tool travel with featured tool

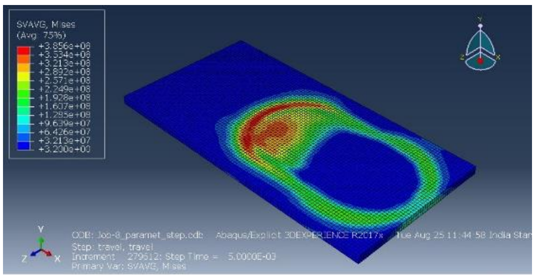

Fig. 4.12 Average Stress at the end of tool travel with the featureless tool

V. CONCLUSION

The current study implements a three-dimensional explicit finite element analysis to evaluate temperature, plastic strain, and average stress generated during FSW of AA6061-T6 plates of 0.5mm thickness. The model simulated plunging and traverse stages involved during the FSW process.

The following conclusions can be obtained on the basis of this study:

1. A Coupled-Eularian Lagrangian (CEL) model was developed using a commercially available ABAQUS dynamic explicit software.
2. The micro featured tool shoulder is producing lower welding temperatures during the process.
3. Plastic strain, in the case of the featureless tool, is higher during plunging, and it is lower during tool travel.
4. In both cases, higher stress is observed at the front of the tool.

Future Scope

- To validate the simulation results by conducting the experimental work.
- To study the material flow and mixing using the simulation.
- To study effects of varying depth of the microgrooves through simulation and experiment.

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