Simulation of Peak Temperature & Flow Stress during FSW of Aluminium Alloy AA6061 for Various Tool Pin Profiles

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Abstract—Amongst the emerging new welding technologies, friction stir welding (FSW), invented and established by The Welding Institute (TWI) in 1991, is used frequently for welding of high strength aluminium alloys such as AA6061, AA6082, AA6351, etc. which are difficult to weld by conventional fusion welding techniques. This paper presents the modelling of FSW for various tool-pin profiles along with simulation of peak temperature induced in plate material and flow stresses generated in the same for friction stir welding of AA6061. The modelling has been carried out by using the FEA software. In present work the three dimensional nonlinear thermal numerical simulations are conducted using Hyper Weld software module for FSW butt joints of AA6061 alloy. Friction stir welding simulation is performed for various tool pin profile at constant 600rpm speed and thermal distribution is analyzed. The results are presented for variations in peak temperatures of aluminium alloy plate as well as flow stresses generated at and around the tool pin during the welding process.

***Index Terms*—FSW, AA6061, modelling & simulation of tools, peak temperature, flow stress**

I. INTRODUCTION

Friction stir welding being a newly developed welding technology in 1991 at TWI of UK [1] utilizes a non consumable tool with a shoulder & a pin projecting from it. As shown in Fig. 1 [2] the pin is plunged into the abutting edges of two plates while rotating and then traversed along the same while the shoulder making firm contact with the surfaces of these two plates.

The frictional heat generated due to rubbing of shoulder & work piece material results in plastic deformation and movement of material from advancing side to retreating side followed by formation of joint behind the tool. The friction stir welding results in substantial change in typical mechanical properties such as strength, ductility, and fatigue and fracture toughness of the joint formed [3]-[9]. For friction stir welding, a few researchers have worked for diversified aspects using various tool pin profiles to study the influence of pin profiles on properties of resulting FSW joint [10], [11]. In FSW joints usually there are four regions, namely, (i) unaffected base metal; (ii) heat effected zone (HAZ); (iii) thermo-mechanically affected zone (TMAZ); (iv) friction stir processed (FSP) zone. The formation of above mentioned regions is affected by the material flow behaviour under the action of rotating non consumable tool. At the same time, the material flow behaviour is predominantly influenced by the FSW tool-pin profiles, FSW tool-dimensions and FSW process parameters [10], [11]. The literature available for study of the effect of tool profiles on FSP zone formation and subsequent effects on peak temperature and flow stress variations for AA6061 aluminium alloy is very limited hence an attempt has been made to understand effect of tool pin profiles on the aforesaid variations using Hyper Works, an efficient FEA tools used for simulation of peak temperature & flow stresses for AA7075-T451 aluminium alloy [12].

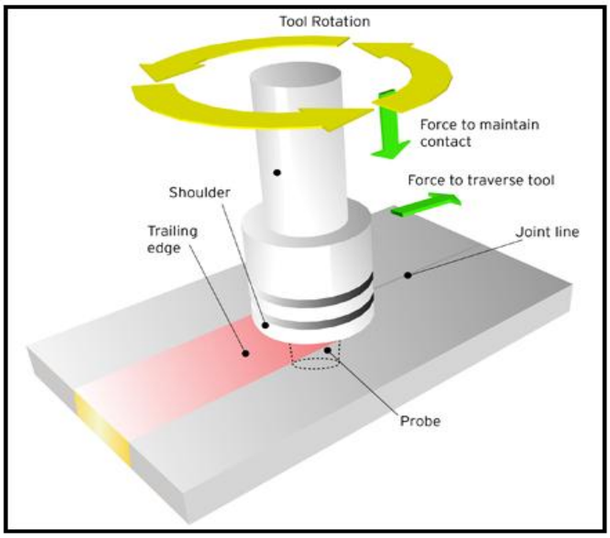

Figure 1. Schematic of friction stir welding [2]

II. MODELLING OF TOOL PIN PROFILES

Manuscript received November 25, 2013; revised February 18, 2014.

doi: 10.12720/ijmse.2.1.67-71

Aluminum alloy AA6061-T6 plates of size 381mm×127mm×5mm thick with the properties as shown in Table I were selected for the simulations & FSW tool of cold work die steel with 1.8% carbon & 11.8% Cr was selected to perform virtual FSW using Hyper Works 11. The tool geometry was selected with cylindrical pin having a shoulder diameter (D=18mm), shoulder length (L=15mm), pin diameter (d=6mm) and pin length (l=4.7mm) as shown in Fig. 2.

TABLE I. PHYSICAL & THERMAL PROPERTIES OF AA6061-T6

Property	**Values**
Density	2.7g/cm3
Melting Point	5820-652 ℃
Modulus of Elasticity	68.9GPa
Poisons Ratio	0.33
Thermal Conductivity	167W/m-K
Specific Heat Capacity	0.869J/g- ℃

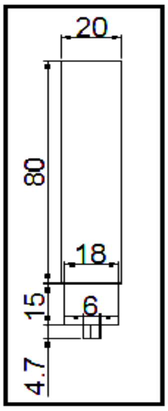

Figure 2. FSW tool shoulder

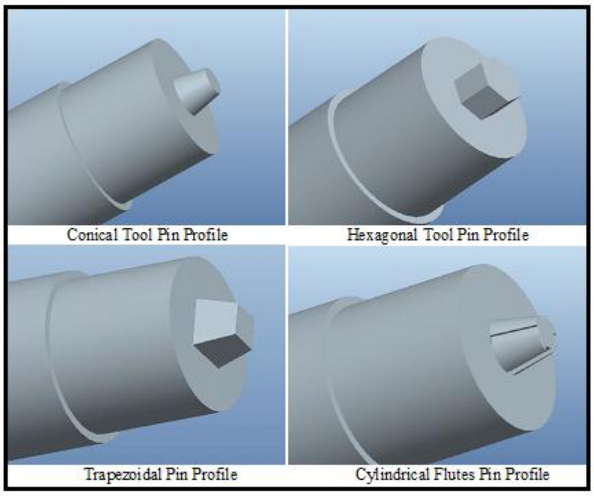

Figure 3. FSW tools with different tool-pin profiles

The FSW tools modelled with four pin profiles as (i) Conical (frustum of a cone), (ii) Cylindrical with flutes at 90° interval, (iii) Hexagonal and (iv)Trapezoidal pin profiles (Fig. 3) were used. The welding speeds were selected as 4.23mm/sec, temperature of plate=20℃ and rotation speed was kept as 600 rpm constant. The tool tilt angle was maintained at 0°. In each weld simulation, the tool plunge was kept constant at 4.7mm with an axial force of 14KN.

III. THERMO MECHANICAL MODELLING

Thermo mechanical modeling and simulation of friction stir welding was done using the finite element software. Computer-aided engineering simulation software by name Altair Hyper works was used for modeling and simulation. A three dimensional thermo mechanical model for butt joining of aluminium plates was developed and solved using HyperXtrude solver. The accurate values of temperature fields, strain rate, effective strain and flow stress during the joint formation were predicted for varying range of process parameters. The thermo mechanical modelling and simulation of the Friction stir welding necessitated the thorough description of certain critical parameters, specifying boundary conditions, post processing.

A. Process Modelling Input

It is very important to prepare correct input for process modelling. Process modelling input is discussed in terms of geometric parameters, process parameters, and material parameters considered during the friction stir welding process.

B. Geometric Parameters

While modelling a friction stir welding process, the starting work piece geometry and the tool geometry need to be defined. The geometric parameters for butt weld joint modelling are length, width and thickness of the plate geometry. Pin diameter, pin height, shoulder diameter and shoulder height are used to define the tool geometry.

C. Process Parameters

The typical process parameters to be considered in a friction stir welding process include,

- The work piece temperature
- Tool translation speed
- Tool rotational speed
- Coefficient of friction between tool and work piece
- Normal force applied by shoulder on the workpiece
- Top and bottom surface heat losses

D. Tool and Work Piece Material Properties

In order to accurately predict the temperature fields and metal flow, it is necessary to use reliable input data. Material properties that relate to both heat transfer and deformation need to be defined. The material properties commonly used for heat transfer modelling are the thermal conductivity, heat capacity, and emissivity of the work piece and tool materials. These properties are usually defined as a function of temperature. The flow stress of the work piece material is very important for the correct prediction of metal flow behaviour. It is usually defined as a function of strain rate and temperature. The Young's modulus, the Poisson's ratio as a function of temperature, and the thermal expansion coefficients of the work and tool materials are important parameters for simulating the friction stir welding process.

E. Element Type

Hex20 elements were used for thermo mechanical modelling; these elements are 3D (2nd order) hexahedra elements with 20 nodes ordered.

F. Boundary Conditions

a. Tool and work piece interface conditions

The tool shoulder provides heating and constrains the deformation zone, while the probe shapes the deformation path that seals the joint and also generates a proportion of the heat, depending on the tool dimensions. The tool rotates at high speeds, such that the peripheral speed of the shoulder and probe is very much greater than the translational speed. Friction stir welding primarily uses viscous dissipation in the work piece material, driven by high shear stresses at the tool/work piece interface.

b. Coefficient friction (μ)

The simplest estimates of Coefficient friction considering a purely rotating tool shoulder (neglecting the translation velocity) by analogy with conventional rotary friction welding.

c. Thermal boundary conditions

The frictional and plastic heat generated during the FSW process propagates rapidly into remote regions of the plates. On the top and side surfaces of the work piece, convection and radiation account for heat loss to the ambient, while the Conduction losses occur from the bottom surface of the work piece to the backing plate.

G. Post Processing

Post processing is an essentially part of any analysis, henceforth with the necessary parameters described and boundary conditions specified the post processing was carried out in the Hyper works software and temperature distribution contours, and flow stress contours were obtained.

IV. RESULTS AND DISCUSSION

The graphical results showing peak temperatures (Fig. 4-Fig. 7) and flow stress distributions (Fig. 8-Fig. 11) obtained by running the simulations on Hyper Works 11.0 indicate the effects of varying welding parameters particularly pin profile in aluminium alloy AA6061. The rotational speed was constant at 600rpm with axial load of 14KN & welding speed of 4.23mm/sec. During the Hyper works simulation on conical pin, the least peak temperature is observed as ~115 ℃ (Fig. 4) with higher flow stress value of 213MPa (Fig. 8). Similarly it is found that comparatively low peak temperature of 300 ℃ (Fig. 5) provides minimum flow stress of 151.8MPa (Fig. 9) for hexagonal pin profile as compared to cylindrical pin profile (Fig. 7 & Fig. 11).

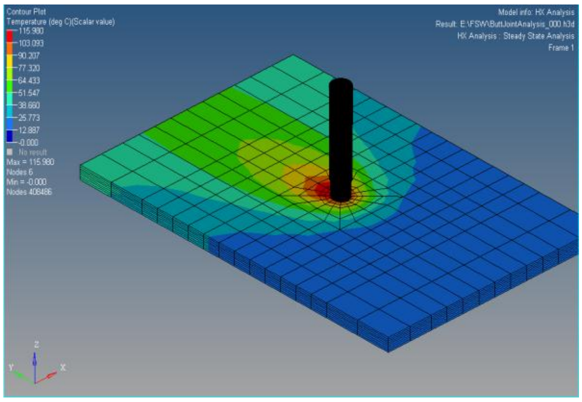

Figure 4. Temperature distribution (Conical)

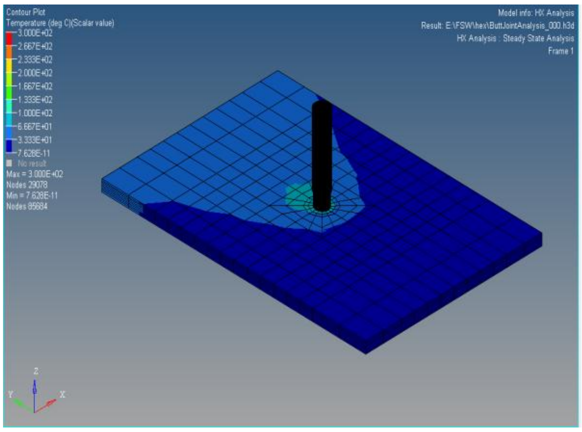

Figure 5. Temperature distribution (Hexagonal)

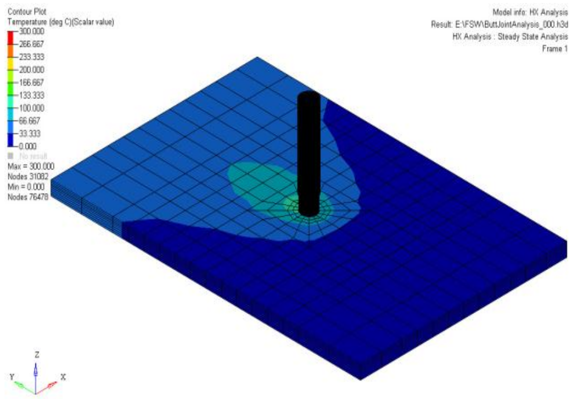

Figure 6. Temperature distribution (Trapezoidal)

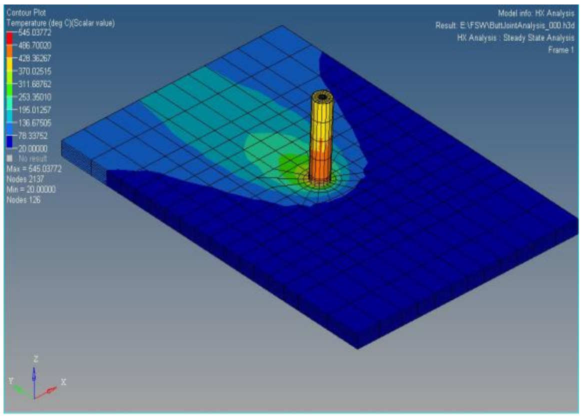

Figure 7. Temperature distribution (Cylindrical)

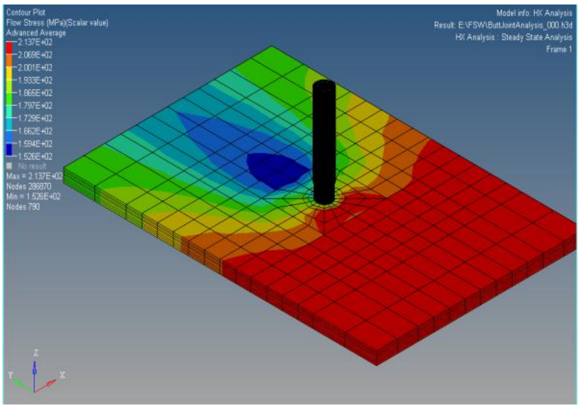

Figure 8. Flow stress distribution (Conical)

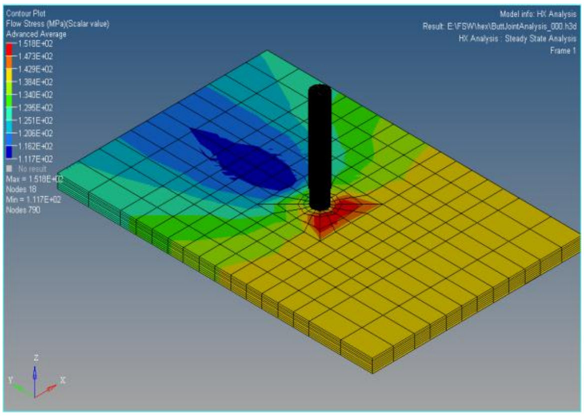

Figure 9. Flow stress distribution (Hexagonal**)**

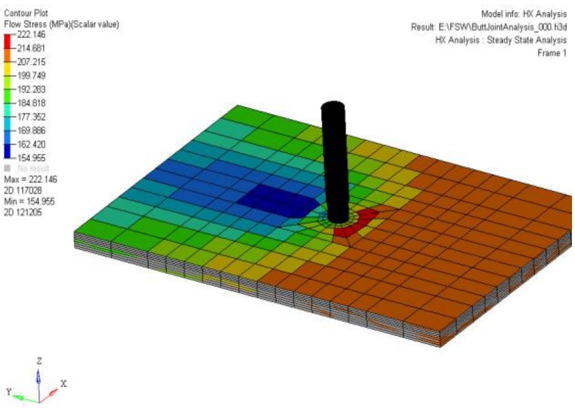

Figure 10. Flow stress distribution (Trapezoidal)

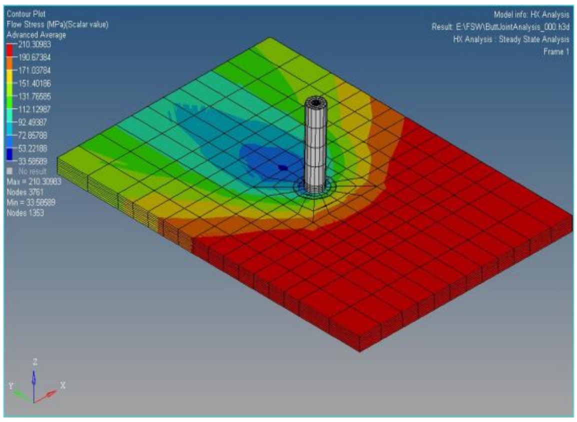

Figure 11. Flow stress distribution (Cylindrical)

Results of simulation in Hyper Works manufacturing solution module for four different tool-pin profiles, peak temperatures and flow stresses obtained for AA6061-T6 aluminium alloy are summarized as in Table II.

TABLE II

Pin Profile	**Pressure (MPa)**	**Peak Temperature (℃)**	**Flow Stress (MPa)**
Conical Pin Profile	879.0	115.98	213.0
Hexagonal Pin Profile	625.9	300.0	151.8
Trapezoidal Pin Profile	881.6	300.0	222.1
Cylindrical with flute Pin Profile	411.37	545.03	210.30

V. Conclusion

FSW simulations performed on Altair's Hyper Weld have opened new horizon of modeling and simulation of joining processes. As a part of virtual laboratory, this software tool can be used to predict the temperature distribution at different zone after FSW process for different parameters.

The following conclusions are arrived at the investigations made from the results of simulations for four different tool-pin profiles.

- During the simulation it is found that comparatively low peak temperature of 300 ℃ provides minimum flow stress of 151.8MPa for Hexagonal pin profile as compared to cylindrical pin profile.
- The peak temperature of ~545 ℃ is achieved for cylindrical pin profile with moderately high flow stresses (~210MPa).
- Similarly, the least peak temperature is observed as ~115 ℃ with still further higher flow stress value of 213MPa in conical pin profile.
- For trapezoidal pin profile, the flow stresses are highest even at a low peak temperature of 300 ℃ which is achieved for hexagonal pin profile too.

Thus, it is concluded that hexagonal pin profile provides better flow of material particles with least resistance amongst all other pin profiles. This works will helps in optimization of process parameters that can be carried out for the selected geometries of tool-pin profile.

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