

Effect of Size of Tool on Peak Temperature & Viscosity during Friction Stir Welding of AA6061-T6 Aluminum Alloy Using HyperWorks

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Abstract: Friction stir welding (FSW) of AA6061-T6 aluminum alloy has been attempted to overcome limitations of fusion welding of the same. The FSW tool, by 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; the former controlling the mechanical properties and later the flow stresses within the material in turn. A software based study to find effect of tool dimensions on the peak temperatures generation during FSW for the said aluminum alloy was carried out to explore the capabilities of the same and provide basis for further research work related to the different aluminum alloys.

Keywords: Friction stir welding, Tool dimensions, AA6061-T6 aluminum alloy, Peak temperature, Viscosity distribution, Flow stresses and Virtual laboratory

I. INTRODUCTION

Invented and developed by The Welding Institute (TWI) in 1991 in UK [1]–[2], the friction stir welding (FSW) has been utilized to a greater extent for welding of various aluminum alloys, especially 6xxx and 7xxx series, to overcome limitations of fusion welding [2]–[3] such as (i) chances for cracking due to wide freezing range (ii) incipient melting and cracking of eutectic phase at the fusion boundaries and (iii) occurrence of micro-porosity leading to a weaker joint or loss of joint-strength. Most of these problems can be prevented from developing by using FSW for aluminum alloys.

Friction stir welding can be accomplished by a non-consumable rotating tool, with a shoulder-pin geometry (Fig.1), inserted at the junction of the solid state work pieces abutting or lapping and then traversed (moved) along the junction line (seam). This produces a weld joint without melting the work-piece material, but by a heavy plastic deformation resulting due to tool rotations & axial force assisted by frictional heat generation during the process [4]–[6]. This heat generation raises the temperature initially at the contact of the tool and work-piece to an extent capable of lowering the material flow stresses which in turn improve plastic flow of work-piece material along the interface [7]. Thus, during FSW process material flows from advancing side to retreating side within a small region approximately equal to diameter of shoulder as shown in figure-1. Within the same region, the material gets forged from its mushy state due to pressure applied by the shoulder. Thus, a solid junction is produced along the interface behind the tool between the two plates [8]. The joint is eventually produced as a result of material movement, which is found to be very complex due to geometrical features of the tool, around the pin [9].

The temperature rise and its distribution in the weld zones become responsible for evolution of the microstructure within the weld that includes grain size, grain boundary character, coarsening and dissolution of precipitates and resulting mechanical properties of the welds when the FSW produces tremendous plastic deformation around the tool and friction between tool and workpiece. It, therefore, becomes necessary to obtain information regarding temperature distribution during FSW. Of course, the direct measurements of temperatures within the stirred zone are quite difficult because of tremendous plastic deformation taking place during FSW due to rotation and translation of the tool.

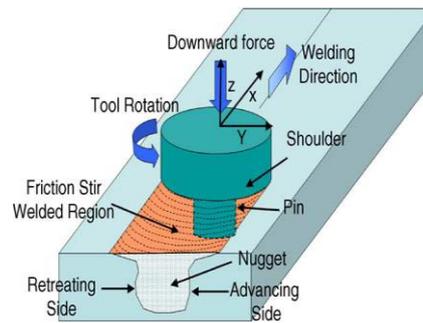


Fig. 1 Friction Stir Welding Schematic Set-up [10]

Despite, the researchers have attempted to estimate the peak temperatures within the stirred zone from the microstructure of the weld [11]–[13] or record the same by embedding thermocouples in the region nearer to rotating pin [14]–[17]. An inverse modelling to estimate indirectly the total frictional heat generated along the interface during the FSW has been reported [18].

Rhodes et al. [11] investigated for microstructural evolution in AA7075-T651 during FSW that larger precipitates dissolve and reprecipitate in the weld center. Therefore, they concluded that maximum process temperatures are between about 400 to 480°C in the AA7075-T651. Murr and coworkers [12]–[13] indicated the non-dissolution of some of the precipitates and suggested a temperature rise roughly to 400°C for AA6061 alloy during FSW. A study of microstructural evolution of AA6063 during FSW was done using transmission electron microscopy (TEM) by Sato et al. [15] and by comparison of these with those obtained by simulated thermal cycles at different peak temperatures they concluded that in the regions of 0 to 8.5, 10.0, 12.5 and 15.0 mm away from weld center, the temperatures were higher than 402, 353, 302°C and lower than 201°C respectively. Tang et al. [16] made an attempt to measure heat input and temperature distribution within friction stir weld by embedding thermocouples in the region to be welded for AA6061-T6 Aluminum alloy having thickness of 6.4 mm. They concluded that (i) Maximum peak temperature was recorded at the weld center and it decreased with increasing distance from the weld centre-line. (ii) At tool rotation speed of 400 rpm and a traverse speed of 122 mm/min, a peak temperature of 450°C was observed at the weld center one quarter from top surface. (iii) The temperature distribution within stirred zone is relatively uniform. Tang et al. [16] investigated further that increasing both tool rotation rate and weld pressure result in an increase in the weld temperature. Further, they [16] studied the effect of shoulder on the temperature field and concluded that contact area & vertical pressure between shoulder and workpiece are much larger than those between the pin and workpiece, also, shoulder has higher linear velocity compared to small radiused pin. Hashimoto et al. [19] reported that the peak temperature in the weld zone increase with increasing the ratio of tool rotation rate to traverse speed for FSW of AA2024-T6, AA5083-O and AA7075-T6. A peak temperature of > 550°C was reported in FSW of AA5083-O at a higher ratio of tool rotation/traverse speed. Frigaad et al. [20] suggested that the tool rotation rate and the shoulder radius are the main process variables in FSW, and pressure P cannot exceed the actual flow stress of the material at the operating temperature if a sound weld without depressions is to be produced. They performed FSW of AA 6082-T6 and AA7108-T79 at constant tool rotation rate of 1500 rpm and a constant welding force of 7 kN at three welding speeds of 300, 480 and 720 mm/min. They revealed that (i) peak temperature of above ~500°C was recorded in the FSW zone, (ii) peak temperature decreased with increasing traverse speeds from 300 to 720 mm/min. For a three dimensional thermal model based on finite element analysis developed by Chao and Qi [21] and Khandkar & Khan [22] showed reasonably good match between the simulated temperature profiles and experimental data for both butt and overlap FSW process. The effect of FSW parameter on temperature was further examined by Arbegast and Hartley [23]. They concluded that for a given tool geometry and depth of penetration, the maximum temperature was a strong function of the rotation rate (rpm) while rate of heating was a strong function of the traverse speed (mm/min). The maximum temperature observed during FSW of various Aluminum alloys is found to be between $0.6T_m$ and $0.9T_m$ which is within the hot working range for those Aluminum alloys, where T_m is melting point of material. Ulysee [24] studied the impact of varying weld parameters on temperature distribution in AA7050-T7451 plate. Khandkar et al. [25] introduced a more comprehensive model of heat input based on the torque of the FSW tool that they used to model temperature history of friction stir welded Aluminum alloy AA6061-T651 plate.

The prime objective of the present paper is to simulate peak temperature, temperature distribution and changes in viscosity at and ahead of the tool during the FSW by changing tool dimensions and using a new software HyperWorks9.0 for AA6061-T6 aluminum alloy which is widely used in applications requiring high strength-to-weight ratio as in aerospace. The alloy AA6061 also possesses good formability, machinability, corrosion resistance and good strength compared to other aluminum alloys. AA6061 can not be fusion welded readily as its mechanical strength gets deteriorated by such welding process.

HyperWorks9.0 provides a special module for friction stir welding under the major module of Manufacturing Solution. It is a very useful meshing tool & can provide solution for a given problem by providing results for various process parameters and welding parameters in terms of temperature, pressure, viscosity, velocities of particles, etc. in the graphical as well as numerical tabular forms [26].

II. EXPERIMENTAL WORK

Aluminum alloy AA6061-T6 plates of size 100 mm x 75 mm x 6 mm with the properties as shown in Table I were selected for the simulations & FSW tool of high carbon high chromium die (HCHCr D2) steel with the properties shown in Table II was used to perform virtual FSW using HyperWorks9.0. The tool geometry was selected with cylindrical pin having a shoulder diameter (D), shoulder length (L), pin diameter (d) and pin length (l) as shown in Table III.

TABLE I
 PHYSICAL & THERMAL PROPERTIES OF AA6061-T6

Property	Values
Density	2.7 g/cm ³
Melting Point	582 ⁰ - 652 ⁰ C
Modulus of Elasticity	68.9 GPa
Poisons Ratio	0.33
Thermal Conductivity	167 W/m-K
Specific Heat Capacity	0.869 J/g- ⁰ C

TABLE II
 PHYSICAL & THERMAL PROPERTIES OF HCHCr D2 DIE STEEL

Property	Values
Density	7.7x 10 ³ kg/m ³
Quenching Temperature	980 ⁰ - 1100 ⁰ C
Modulus of Elasticity	210 GPa
Hardness (hardened)	64 HRC
Thermal Conductivity	20 W/m-K
Specific Heat Capacity	461 J/kg-K

TABLE III
 TOOL GEOMETRY FOR SIMULATION

Sr. No.	Shoulder Diameter (D),mm	Shoulder Length (L),mm	Pin Diameter (d),mm	Pin Length (l),mm	Tool Material
1	24	15	6.0	5.5	HCHCr
2	30	20	10.0	9.5	HCHCr

The simulations were performed by varying FSW parameters as tool rotational speed & tool traverse speed as shown in Table IV for two sizes of tools mentioned above in Table III with the help of software HyperWorks9.0.

TABLE IV
 FSW PARAMETERS FOR AA6061-T6 PLATES

Sr. No.	Tool Geometry (Table III)	Tool Rotational Speed N, RPM	Tool Traverse Speed v, mm/min
1	Sr. No. 1	1000	253.8
2	Sr. No. 1	1400	153.8
3	Sr. No. 2	1000	253.8
4	Sr. No. 2	1400	153.8

III. RESULTS & DISCUSSIONS

The graphical results showing temperature distribution and viscosity distribution obtained by running the simulation on HyperWorks9.0 indicate the effects of varying welding parameters, namely tool rotational speed and tool traverse speed. The results also represent the effects of changes in tool dimensions for the same tool geometry & tool material. Fig. 2(a) and Fig. 2(b) clearly indicate the difference in the temperature developed and viscosity gained by the plate material particularly in advance of the tool position, for combination shown at Sr.No.1 in Table IV.

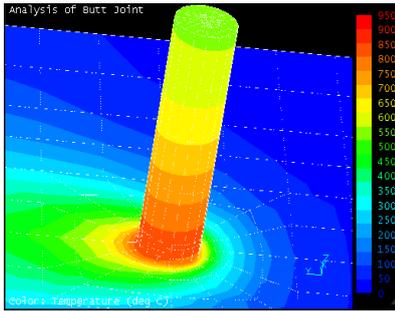


Fig. 2(a): Temperature for Sr.No.1
 (At N = 1000, v = 253.8 mm/min)

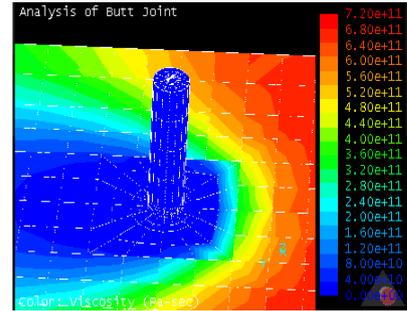


Fig. 2(b): Viscosity for Sr.No.1
 (At N = 1000, v = 253.8 mm/min)

Similarly, Fig. 3(a) and Fig. 3(b) indicate the difference for the same two parameters at the same tool position, for combination shown at Sr. No. 3 in Table IV.

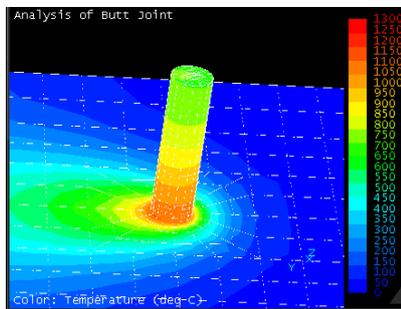


Fig. 3(a): Temperature for Sr.No.3
 (At N = 1000, v = 253.8 mm/min)

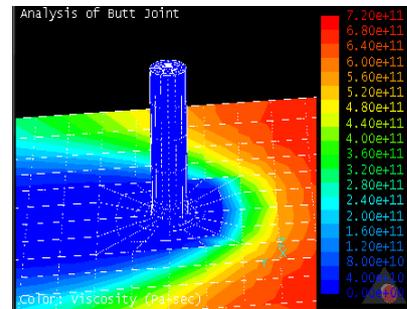


Fig. 3(b): Viscosity for Sr.No.3
 (At N = 1000, v = 253.8 mm/min)

Similarly, simulation experiments for Sr.No.2 & 4 of Table IV were carried out and results shown in figures 4(a), 4(b), 5(a) and 5(b) in a similar way.

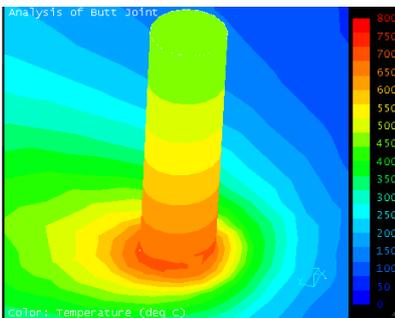


Fig. 4(a): Temperature for Sr.No.2
 (At N = 1400, v = 153.8 mm/min)

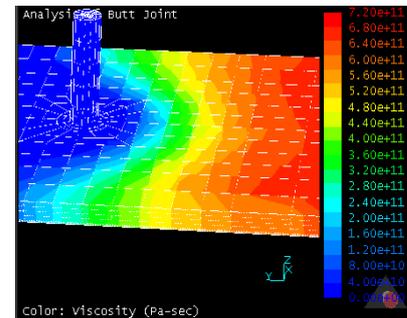


Fig. 4(b): Viscosity for Sr.No.2
 (At N = 1400, v = 153.8 mm/min)

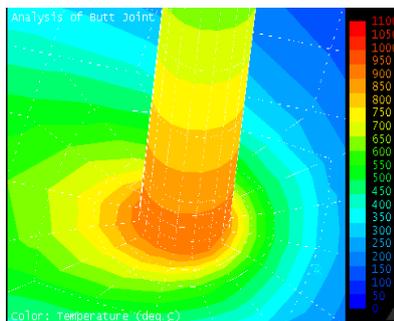


Fig. 5(a): Temperature for Sr.No.4
 (At N = 1400, v = 153.8 mm/min)

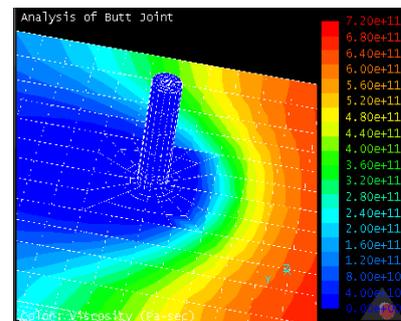


Fig. 5(b): Viscosity for Sr.No.4
 (At N = 1400, v = 153.8 mm/min)

IV. CONCLUSION

It can be concluded that variations in dimensions of FSW tools along with tool rotational speed, tool traverse speed by keeping the geometry same have prominent effects on temperature history & viscosity developed during FSW of AA6061-T6 aluminum alloy. The induced temperatures and viscosities in turn determine the state of material. It is observed from the distribution results that peak temperature increases by increasing the size of the FSW tool and distribution of viscosity changes accordingly. The viscosity is found less nearer to the tool where temperature is higher; this assists in easy flow of plasticized material of the plate from advancing side to retreating side. Thus, temperatures developed, governed by dimensions of tool, greatly affect the viscosity variations within the material being welded and the viscosity induced governs the flow of material and thus, contribute in establishing a microstructure which in turn dictates the mechanical properties of the joint produced. As the temperature history is simulated using HyperWorks9.0, the results for temperatures can be validated by experimentally measuring the same using a sophisticated measuring device capable of memorizing the output data in various forms. Also, viscosity distribution may be indirectly validated by simulating flow patterns on some other software for measured temperatures. Simulations performed on FEA software (HyperWorks9.0) opens the new horizon of modelling friction stir welding process in virtual laboratory and help predict the mechanical properties of FSW-joints.

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