Heat Transfer Analysis In Friction Stir Welded Aluminium Alloys

Ritesh Jaiswal[1], Rajnish Singh[2]
Mechanical Engineering Department, Kamla Nehru Institute of Technology, Sultanpur -228118-India[1,2]

***Abstract-* In this work, die steel tool is used to join the two aluminium sheet together on a drilling machine. For this, a cylindrical shaped tool was manufactured. This tool is then clamped into the drilling machine tool post. This rotating tool is then inserted into the work piece thus generating heat due to friction. The plastic deformation of aluminium starts near vicinity of tool impression. The tool transferred the soften material from tip to plunger. The plunger is in contact with the Aluminium sheet. Soften material is forged on the sheet with the help of plunger and thus creating a solid phase joint between the Aluminium sheets.**

Three-dimensional numerical modelling was performed on Ansys software. A three-dimensional heat transfer model is used to solve the problem of friction stir welding. This model is solved by using the energy conservation equation. This model involves the heat generated at interface of the work piece and the rotating tool. The steady-state heat transfer equation was used to study the problem. The numerically computed and the measured value is compared to validate the results.

I. INTRODUCTION

Before the 1990s, we had various welding technologies such as gas welding, arc welding, etc. to join the one substance to another which may be similar or dissimilar with having different mechanical, chemical and physical properties. But in these welding process, many disadvantages have been found such as hot cracking, porosity and residual stresses[1]. The main problem was found is the formation of an oxide layer on the surface of Aluminium during arc welding. This leads to the hardening of the Aluminium surface. This hardened surface is very difficult to machine. So in 1991, W. M. Thomas at The Welding Institute (TWI) of UK discovered the friction stir welding (FSW). FSW is a method of bonding two similar or dissimilar materials in a solid-state. In this process, metal is rubbed on the surface of other material. Due to this rubbing heat is produced. This heat energy is concentrated at a point which softens the material and material gets plasticized. As the material gets plasticized a compressive force is applied and both the parts are joined to each other[2]. This joined work piece is free from any defects such as porosity, hot cracks, etc.

Many studies have been performed in understanding the process of FSW and modelling of friction welding. R Singh et al. performed an experiment on friction stir spot welding using a tool of cylindrical shaped. Various parameters such as rotational speed, feed rates, axial force, etc. are studied on the heat-affected zone of friction stir welding. It was concluded, more heat is generated at a very high rotational speed at the tool shoulder diameter. lt of FSW was analyzed by Taguchi robust design method. Mc Andrew et al. studied the linear FSW for the fabrication of titanium alloy disks. Linear friction welding of Ti alloy has three different zones 1. Weld canter zone (WCZ), 2. Thermo mechanically affected zone (TMAZ), 3. Heat affected zone (HAZ). A strong texture is found in WCZ while alternating bonds of transverse textures are present in TMAZ.[4] Jedrosiak et al. presented thermal modelling of linear FSW by using the finite element method (FEM) on a welded joint of Ti6Al4V alloy. The temperature region was found to a thin layer around the interface. 20% discrepancy was found when the experimental value was compared with the equilibrium stage[2]. Lesniewski et al. studied the various welding parameters and variation of temperature, stress, and strain. The temperature distribution in the pseudo-alloy of titanium-tungsten is radically distributed with a decrease in difference in case of the friction welding process. The thermal field during the friction welding process was found to be changed with the change in the coefficient of friction[5]. Chu. Q. et al. produced a joint of AA2198 using friction stir spot welding. It was observed from the FSW that centrifugal effect exists. [6].Zhang B. et al. in their research work analyzed the thermal behavior and mechanical properties of friction welding. Hook defect as the crack is found during the simulation of the model[7]. Esther T. Akinlabi et al. made their study on characterization of material behavior of FSW. From this research, it was concluded that at rotational speed 1600 rpm the weld zone has the highest shear stregth[8]. Bilal Ahmad et al. performed their research work on friction stir welding which is an advanced joining process. it was concluded that the heat-affected zone is small in fast weld model and large in slow weld model[9]. Shokri V. et al. used a thermomechanical simulation to predict residual stress and material flow. The optimum condition for friction stir welding was found that rotational speed is 1200 rpm, tool offset 0.5 mm and travel speed of 30 mm/min[10]. Ahmed Ramadan et al. made an analytical model to study the heat generation in FSW. It was concluded from the experiment that less temperature is generated when an eccentric cylindrical pin is used as compared to a cylindrical pin[11]. Pankaj Sahlot et al. performed the numerical modeling of FSW of copper. Tensile strength of welded material increases as tool rotational speed is increased[12]. C.M. Chen et al. pointed out the advantages of friction stir welding over the conventional fusion welding process. It was concluded from the work that maximum temperatures are achieved just beyond the shoulder edge in both longitudinal and lateral direction[13].

II. EXPERIMENTAL SETUP

Friction stir spot welding was performed on drilling machine to weld the Al 6061 alloy in butt configuration. The drilling machine can be rotated in the lateral and longitudinal direction both. The workpiece used for the welding was an aluminum alloy which has a thickness of 3.0 mm, with a length of 300 mm and width of 50 mm each. The tool material selected for the welding was Die Steel. As the strength of die steel is very high so it can be easily penetrated into the aluminum and welding can be performed easily. The tool has flat shoulder with 18 mm shoulder diameter and cylindrical pin of 2.5 mm length and 4mm diameter. A bed of cast iron of dimension 320 mm length, 140 mm width and 20 mm height was made to clamp the workpiece during welding. The bed was prepared using a shaper machine. The thermocouple is used for measuring the value of temperature at a different point during the welding. Tools, machine and different materials which are used are listed below:

2.1 Drilling machine

The drilling machine used has 3 phase AC power source. The gearbox attached in a drilling machine is used to change the spindle speed. [14] The spindle speed of the drilling machine used is 1250 rpm, 1300rpm and 1400 rpm.

2.2 Die Steel Tool

Die steel material is selected for the tool making. The diameter of the shoulder is kept 18 mm. A tip is made which has a dimension 4mm diameter and 2.5 mm in length. As shown in figure 1. The chemical composition of die steel is tabulated below in the table 1:

Table 1: Composition of die steel

Elements	Carbon	Silicon	Manganese	Chromium	Molybdenum	Vanadium
Percentage	1.50 %	0.30 %	0.40 %	12.00 %	1.00 %	0.90 %

Figure 1: Die steel tool

2.3 Al 6061 plate

Aluminum strip is used for FSW. The melting point temperature of aluminum is approximately 660 degree Celsius. The dimension of the aluminum strip which was used for welding purpose was 300 mm in length, 50 mm width and 3 mm thick. Various elements present in Al 6061 alloy is presented in the table 2 below:

Table 1: Composition of Al 6061 in weight percentages [15]

Elements	Cr	Mg	Mn	Cu	Zn	Fe	Si	Ti	Al
Percentage (%)	0.26	1.08	0.11	0.34	0.223	0.66	0.55	0.16	Balance

2.4 Workpiece Clamp

Figure 2: Clamping of Al strip on cast iron bed

Cast iron plate is used to support the aluminum strip during friction spot welding. The dimension used for bed is 320 mm in length, 140 mm in width, and 20 mm in height as shown in figure 2. The radial drilling machine was converted into friction stir spot welding setup as shown in figure 3. The drilling machine was configured as four steped rotational speed mentioned in the table 3. The spot welded plate is shown in figure 4.

2.5 Welding Setup

Figure 3: Friction welding of Al 6061

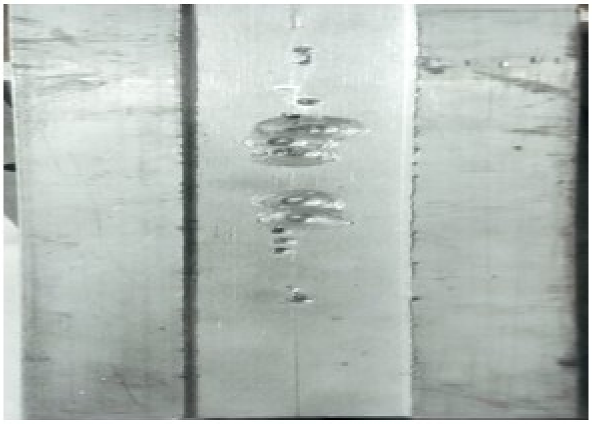


Figure 4: Friction welded Al 6061 alloy

During the FSW of aluminum alloy, the tool is inserted into workpiece for the welding purpose. The tool heats workpiece due to frictional heat developed and it is heated below its melting point. Tool mix the soft material of both the plate and pressure is applied to join this portion. So the total area deformed in the friction spot welding is an area where tool is in contact with work piece.

The line was made with scriber which wa at 12 mm distance from the centre line. The thermocouple was placed at that position to monitor the temperature scale which is shown in the table3.

Table 3: Fusion temperature of Al 6061 for different spindle speed

Spindle Speed	Temperature at radius +12 mm (in ^{0}C)
1250 rpm	138
1300 rpm	146
1400 rpm	170
1500 rpm	173

III. MODELING AND SIMULATION

A thermo-mechanical transient based model is used on Ansys to simulate the FSW of Al6061. To study the simulation a mesh-based model is created on Ansys. The workpiece is partitioned in two halves and one part is taken into consideration for the study. Since both parts are symmetric to one another to studying one part is sufficient to get the simulation result.

3.1 Mathematical model

For mathematical model following assumption are made.

- The heat developed between tool and workpiece is due to friction.
- Die steel tool is cylindrical in shape and no thread is made on the tip of the tool.
- If the local temperature reaches to melting point temperature of aluminum then no heat flows into it.

3.2 Governing equation

During the FSW, the tool moves with constant speed along joining line of two plates. A three-dimensional heat transfer model is used to solve the problem of FSW. This model is solved by using the energy conservation equation. This model involves the heat developed at workpiece by the tool. The heat transfer equation in steady state is given as:

$$\frac{\partial}{\partial x_i}\left(-k\frac{\partial T}{\partial x_i}\right)+\rho C_p U\frac{\partial T}{\partial x_i}=Q \qquad (1)$$

Where K is thermal conductivity of aluminum, is the material density, U is flow velocity of material, T is the temperature of the material, Q is heat input of welding and is the specific heat of material at constant pressure.

3.3 Heat generation

Total heat developed during the FSW of Al6061 is sum of total heat generated by the tool pin and tool shoulder.

$$Q = Q_{shoulder} + Q_{pin} \qquad (2)$$

3.4 Heat input by tool shoulder

It is assumed that the heat generated at the interface of tool and workpiece is due to friction between them. The local heat generation by tool shoulder is calculated by following relation [16].

$$q_{fi} = 2\pi\mu F_n R_i n \qquad (3)$$

Here Ri is the distance from the tooltip where the temperature is measured, n is rotational speed and Fn is the axial downward force. The value of coefficient of friction is taken 0.3 for this work.

3.5 Heat input from the tool pin

The heat generation by tool pin consists of three stages: (1) heat due to shearing of workpiece; (2) heat due to thread present on tool pin; (3) heat generation by the vertical surface of tool pin. The heat generated by the tool pin is calculated by the relation given by the Colegrove [17]. Colegrove numerical relation is given as:

$$Q_{pin} = 2\pi r_p h\frac{Y(T)}{\sqrt{3}}V_m + \frac{2\mu k Y r_p h V_{rp}}{\sqrt{3(1+\mu^2)}} + \frac{4F_p \mu V_m \cos\theta}{\pi} \qquad (4)$$

Here

$$\theta = 90^0 - \lambda - \tan^{-1}(\mu)$$

$$V_m = \frac{\sin\lambda}{\sin(180^0-\theta-\lambda)}v_p$$

$$V_{rp} = \frac{\sin\theta}{\sin(180^0-\theta-\lambda)}v_p$$

And

$$v_p = r_p w$$

Here is the radius of the tool pin, Y(T) is avg. shear stress of material and it is a function of temperature, h is the thickness of the workpiece, Fp is the axial force, is helix angle of thread, since tip of the tool is cylindrical without thread so value of helix angle is 0 or 90, is the coefficient of friction between the workpiece and the tool. A cylindrical tool is used without thread for this work so heix angle is taken zero.

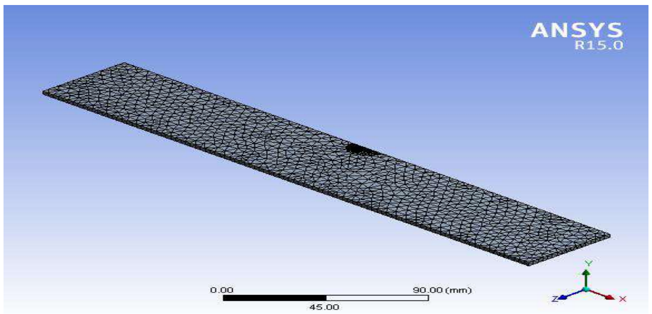


Figure 5: Meshing of workpiece

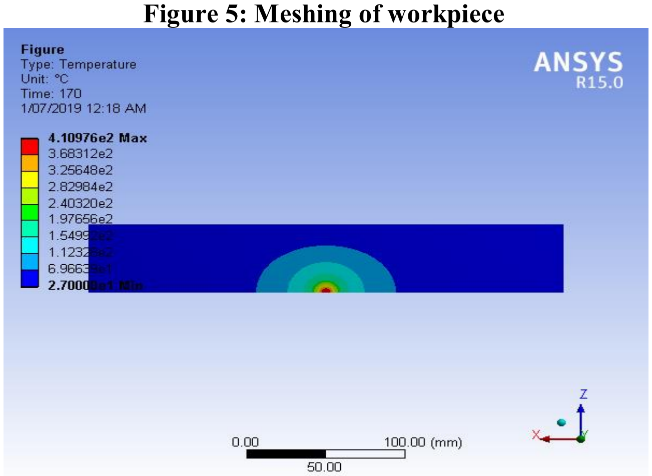
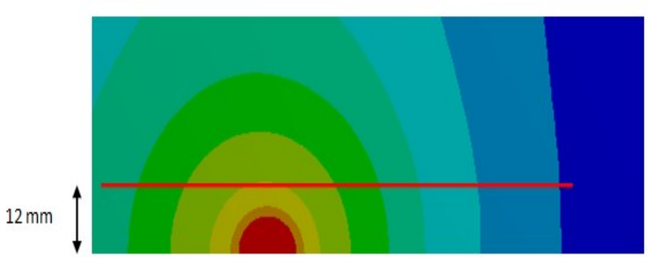


Figure 6: Temperature distribution in the plate

4.2 Variation of temperature with the distance of the plate of friction spot welding of Aluminum

From the figure 7, it is clear that temperature at left and right end of plate is ambient temperature. As we move from the left end to the center the temperature increases. While moving from the centre to the right end the temperature distribution decreases. Similar case was also observed in case of 1300 rpm rotational speed as shown in figure 8.



At this point, the temperature developed with the distance is given as

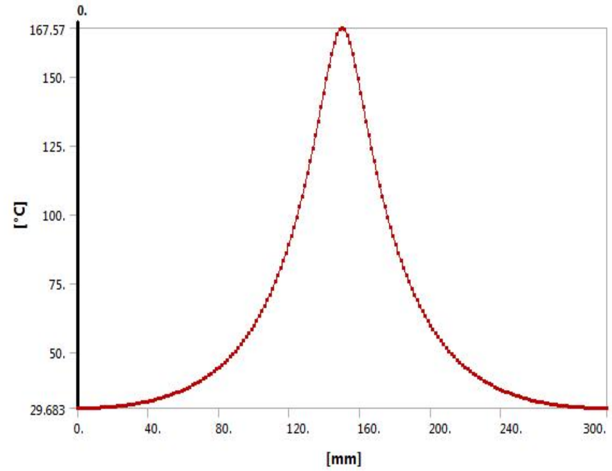


Figure 7: Variation of Temperature With the Distance At 1500 Rpm

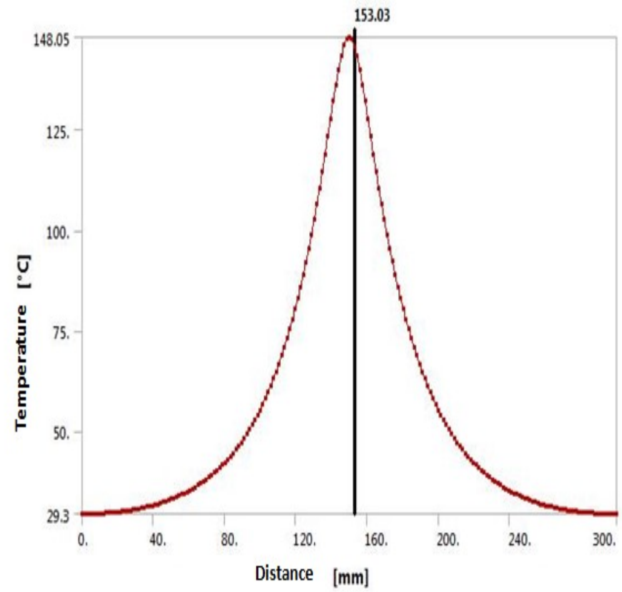


Figure 8: Variation of Temperature With Distance at 1300 Rpm

4.3 Comparison of Numerical Model with an experimental model for FSW of Al-6061

The thermocouple is placed at a location of 12 mm away from the welding line. Temperature is measured at this point using thermocouple. The measured temperature by thermocouple and ansys simulation were compared for rotational speed of 1300 and 1500 rpm. It was observed that experimental temperature were found lower than the numerical simulation.The figure 9 and 10 depicts a comparison of computed and measured values of peak temperatures during FSW of aluminum. The experimental and simulated value of temperature on Ansys R19.2 differ from +5 to -5%. This difference of value is may be due to material flow calculations, boundary condition variations or machine and manual error.

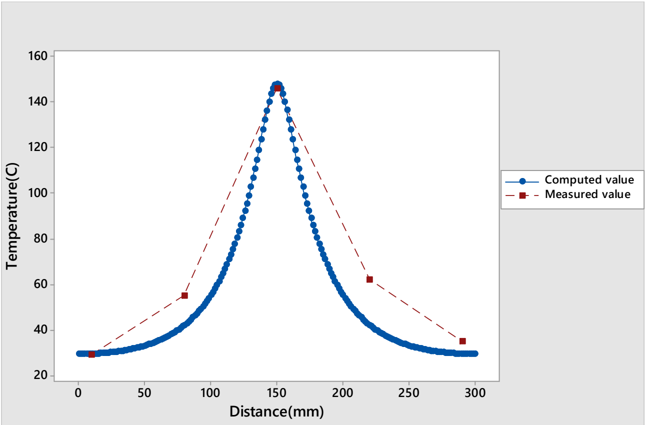


Figure 9: Variation between the computed and measured temperature at 1300 rpm.

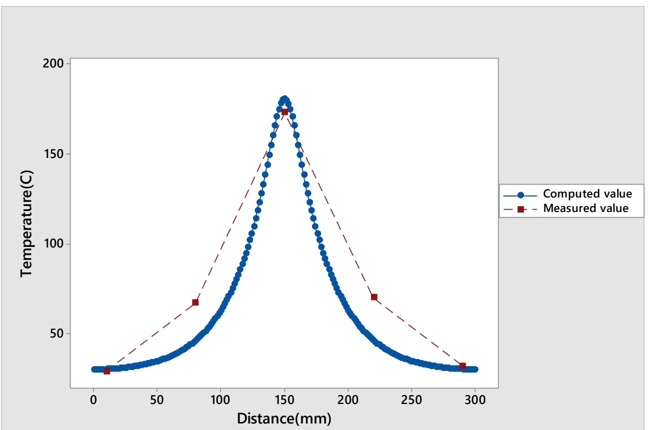


Figure 10: Variation between the computed and measured temperature at 1500 rpm.

IV. CONCLUSION

From the above work of FSW of Al6061 following conclusion are drawn:

1. 3-D heat transfer model is used to predict the three-dimensional temperature distribution during FSW of Al 6061 alloy.
2. The simulated temperature on Ansys and the experimentally measured temperature vary with +5 to -5%.
3. Maximum heat is generated at the center and it decreases towards the outer periphery.
4. It is found from the experimental result that the temperature of fusion in the workpiece increases with increases in the rotational speed of the tool.

REFERENCES

[1] X. Yang et al., "Finite element modeling of the linear friction welding of GH4169 super alloy," Mater. Des. vol. 87, pp. 215–230, 2015.

[2] P. Jedrasiak, H. R. Shercliff, A. R. McAndrew, and P. A. Colegrove, "Thermal modelling of linear friction welding," Mater. Des., vol. 156, pp. 362–369, 2018.

[3] S. Kumar, R. Singh, R. Jaiswal, and A. Kumar, "Optimization of process parameters of electron beam welded Fe49Co2V alloys," Int. J. Eng. Trans. B Appl., vol. 33, no. 5, pp. 870–876, 2020.

[4] A. R. McAndrew, P. A. Colegrove, C. Bühr, B. C. D. Flipo, and A. Vairis, "A literature review of Ti-6Al-4V linear friction welding," Prog. Mater. Sci., vol. 92, pp. 225–257, 2018.

[5] J. Leśniewski and A. Ambroziak, "Modelling the friction welding of titanium and tungsten pseudoalloy," Arch. Civ. Mech. Eng., vol. 15, no. 1, pp. 142–150, 2015.

[6] Q. Chu, X. W. Yang, W. Y. Li, A. Vairis, and W. B. Wang, "Numerical analysis of material flow in the probeless friction stir spot welding based on Coupled Eulerian-Lagrangian approach," J. Manuf. Process., vol. 36, no. July, pp. 181–187, 2018.

[7] H. J. Zhang, H. J. Liu, and L. Yu, "Thermal modeling of underwater friction stir welding of high strength aluminum alloy," Trans. Nonferrous Met. Soc. China (English Ed., vol. 23, no. 4, pp. 1114–1122, 2013.

[8] E. T. Akinlabi, O. Kazeem, E. Muzenda, and A. Stephen, "ScienceDirect Material behaviour characterization of Friction Stir Spot Welding of Copper," Mater. Today Proc., vol. 4, no. 2, pp. 166–177, 2017.

[9] B. Ahmad, A. Galloway, and A. Toumpis, "Advanced numerical modelling of friction stir welded low alloy steel," J. Manuf. Process., vol. 34, no. July, pp. 625–636, 2018.

[10] V. Shokri, A. Sadeghi, and M. H. Sadeghi, "Thermomechanical modeling of friction stir welding in a Cu-DSS dissimilar joint," J. Manuf. Process., vol. 31, pp. 46–55, 2018.

[11] R. Xiao and X. Zhang, "Problems and issues in laser beam welding of aluminum-lithium alloys," J. Manuf. Process., vol. 16, no. 2, pp. 166–175, 2014.

[12] P. Sahlot, A. K. Singh, V. J. Badheka, and A. Arora, "Friction Stir Welding of Copper: Numerical Modeling and Validation," Trans. Indian Inst. Met., 2019.

[13] C. M. Chen and R. Kovacevic, "Finite element modeling of friction stir welding - Thermal and thermomechanical analysis," Int. J. Mach. Tools Manuf., vol. 43, no. 13, pp. 1319–1326, 2003.

[14] "Drilling Machine." [Online]. Available: http://sainsmechanical.blogspot.com/2011/12/drilling-machine.html. [Accessed: 24-May-2019].

[15] P. Chauhan, R. Jain, S. K. Pal, and S. B. Singh, "Modeling of defects in friction stir welding using coupled Eulerian and Lagrangian method," J. Manuf. Process., vol. 34, no. November 2017, pp. 158–166, 2018.

[16] M. Song and R. Kovacevic, "Heat transfer modelling for both workpiece and tool in the friction stir welding process: A coupled model," Proc. Inst. Mech. Eng. Part B J. Eng. Manuf., vol. 218, no. 1, pp. 17–33, 2004.

[17] P. Colegrove, "Three dimensional flow and thermal modeling of the friction stir welding process," Int. Symp. Frict. Stir Welding, Sweden, 2000.