Modeling, simulation and experimental validation for friction stir welding

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***Abstract*— Friction stir welding are relatively new solid-state joining technique which is widely adopted in different industry fields to join different metallic alloys that are hard to weld by conventional fusion welding. Friction stir welding is a highly complex process comprising several highly coupled physical phenomena. The complex geometry of some kinds of joints and their three dimensional nature make it difficult to develop an overall system of governing equations for theoretical analyzing the behavior of the friction stir welded joints. This study aims to model friction stir welding of the aluminum alloys using the finite element method. For this purpose, transient thermal finite element analyses shall perform in order to obtain the temperature distribution in the welded aluminum plate during the welding operation. Three-dimensional models are carried out by using ANSYS commercial software's. APDL (ANSYS Parametric Design Language) code is developed to model moving heat source and change boundary conditions. The temperature distribution across the work piece depends on the amount of heat conducted into the plate. This in turn influences the material flow, microstructure and mechanical properties of the weld zone. To predict and control the temperature distribution during FSW process with reference to tool geometry, rotational and welding speed, it is necessary to carryout detailed thermal modeling of FSW.**

Index Terms—Friction Stir Welding (FSW), ANSYS Parametric Design Language (APDL).

I. Introduction

Friction stir welding (FSW) is a recently emerged solid-state joining technology patented by The welding Institute (TWI) in 1991.FSW is a solid state joining process in which a specially designed non consumable rotating tool is used to weld the plates generated in friction stir welding process is primarily by friction between tool and work piece and the plastic deformation of the work piece material. The amount of heat generated is due to the friction and plastic deformation at the tool-work piece interfaces that depends on tool geometry and welding parameters. The heat generated is conducted to both work piece as well as the tool. The rate of heat transfer depends on the heat generation rate, conduction within the material and convection to the ambient. The temperature distribution across the work piece depends on the amount of heat conducted into the plate. This in turn influences the material flow, microstructure and mechanical properties of the weld zone. To predict and control the temperature distribution during FSW process with reference to tool geometry, rotational and welding speed, it is necessary to carryout detailed thermal modeling of FSW. FSW consists mainly in three phases, in which each one can be described as a time period where the welding tool and the work piece are moved relative to each other. In the first phase, the rotating tool is vertically displaced into the joint line (plunge period). This period is followed by the dwell period in which the tool is held steady relative to the work piece but still rotating. Owing to the velocity difference between the rotating tool and the stationary work piece, the mechanical interaction produces heat by means of frictional work and material plastic deformation. This heat is dissipated into the neighboring material, promoting an increase of temperature and consequent material softening. After these two initial phases the welding operation can be initiated by moving either the tool or the work piece relative to each other along the joint line. In FSW heat is not additionally given but generate by application of pressure and movement of tool i.e. rotational speed and transverse feed. Friction welding is a form of solid state welding process, which relies on the formation of molten bridge, deformation and on the flow of metal. The basic principle of friction welding involves simultaneous application of pressure and relative motion, generally in a rotational mode, between the components to be joined. The frictional heat thus generated raises the interface temperature of the components to their melting points while the applied pressure perpendicular to the plane of motion serves to extrude the heated material including any dirt and oxide films from the interface, bringing the components to be joined into intimate contact. FSW is a highly complex process comprising several highly coupled (and non-linear) physical phenomena. These phenomena include large plastic deformation, material flow, mechanical stirring, surface interaction between the tool and the work piece, dynamic structural evolution and heat generation resulting from friction and plastic deformation. Multiple parameters greatly influence the quality of the FSW joints. The behavior of the FSW joints is not only influenced by the geometry of the tools and the joints but also by different process parameters. The complex geometry of some kinds of joints and their three dimensional nature make it difficult to develop an overall system of governing equations for predicting the behavior of the FSW joints. In addition, material non-linearity due to plastic behavior is difficult to incorporate because the analysis becomes very complex in the

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mathematical formulation. The experiments are often time consuming and costly. To overcome these problems, numerical analysis has frequently been used since the 2000s.

II. LITERATURE REVIEW

Friction stir welding is a novel solid-state joining process may have significant advantages compared to the fusion processes as follow: Joining of conventionally non-fusion weld able alloys, reduced distortion and improved mechanical properties of weld able alloys joints due to the pure solid-state joining of metals. In a typical FSW, a rotating cylindrical pin tool is forced to plunge into the plates to be welded and moved along their contact line. During the welding, heat is generated by contact friction between the tool and work piece softens the material. Since no melting occurs during FSW, the process is performed at much lower temperatures than conventional welding techniques. Because of the highest temperature is lower than the melting temperature of the material, FSW yields fine microstructure. Although it is a new welding technology, the FSW has been extensively studied both numerically and experimentally. Chen and Kovacevic studied on the finite element analysis of the thermal history and thermo mechanical process in the butt-welding of aluminum alloy 6061- T6. Buffa *et al.* proposed a 3D FEM model for the FSW process that is thermo-mechanically coupled and with rigid-viscoplastic material behavior. Nandan *et al.* modeled three-dimensional visco-plastic flow and temperature field during FSW of 304 austenitic stainless steel mathematically. Chao *et al*. formulated the heat transfer of the FSW process into two boundary value problems (BVP)-a steady state BVP for the tool and a transient BVP for the work piece. They carried out the finite element analyses to determine the heat flux generated from the friction to the work piece and the tool. Zhang *et al.* developed solid mechanics-based finite element models and computational procedures to study the flow patterns and the residual stresses in FSW. They presented two-dimensional results of the material flow patterns and the residual stresses and investigated the flow of metal during FSW. They showed that the flows on the advancing side and retreating side are different. They investigated the residual stresses of the welded plate. They concluded that with the increase of the translational velocity, the maximum longitudinal residual stress can be increased. Hamilton *et al*. developed a thermal model of FSW that utilizes a new slip factor based on the energy per unit length of weld. The slip factor was derived from an empirical, linear relationship observed between the ratio of the maximum welding temperature to the solidus temperature and the welding energy. Song and Kovacevic presented a three-dimensional heat transfer model for FSW. They introduced a moving coordinate to reduce the difficulty of modeling the moving tool and considered heat input from the tool shoulder and the tool pin in their model. The finite difference method was applied in solving the control equations. They concluded that preheat to the work piece is beneficial to FSW. Rajamanickam *et al.* investigated the effect of process parameters such as tool rotation and weld speed on temperature distribution and mechanical properties of aluminum alloy AA2014 joined by friction stir welding. A three dimensional transient thermal model using finite element code ANSYS was developed and experimentally validated to quantify the thermal history. Soundararajan *et al*. developed a thermo-mechanical model with both tool and work piece using mechanical loading with thermal stress to predict the effective stress development at the bottom of work piece with uniform boundary conditions. They used the stress to define the adaptable contact conductance values in the thermal model at the work piece-backing plate interface and measured the temperatures at various locations during experiment using thermocouples to validate the finite element model predictions. In the present study, the modeling of FSW process is carried out using the finite element method. Transient thermal finite element analyses are performed in order to obtain the temperature distribution in the welded aluminum plate during the welding operation. A moving heat source with a heat distribution simulating the heat generated from the friction between the tool shoulder and the work piece is used in the heat transfer analysis. Three-dimensional models are carried out by using ANSYS and HyperXtrude commercial software's. APDL (ANSYS Parametric Design Language) code is developed to model moving heat source and change boundary conditions. The usage of APDL code removes the necessity of using ANSYS user interface. Advantage of ANSYS software is that the temperature outputs can be obtained at every desired time step.

III. METHODOLOGY

Project comprises of analytical, experimental and simulation approach. The basic idea behind the project is to design of friction stir welding to overcome on the problems those are faced during conventional welding. Planned methodology consists of: Study the effect of the microstructure and wear properties.

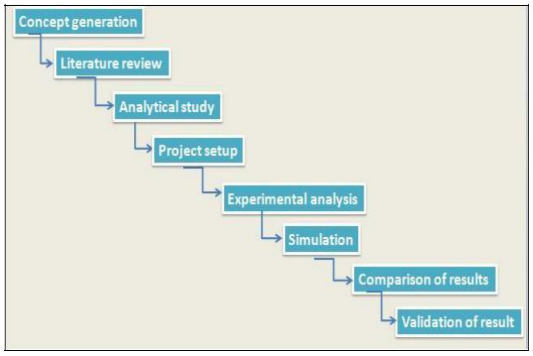


Fig.No.1. Research Methodology

1. Study design parameters of FSW.
2. Developing mathematical model of FSW
3. Designing and manufacturing of friction stir welding for testing
4. Simulation analysis using ANYSI
5. Comparison and validation of results

A. Process

The working principle of Friction Stir Welding process is shown in Fig. 2. A welding tool comprised of a shank, shoulder, and pin is fixed in a milling machine chuck and is rotated about its longitudinal axis. The work piece, with square mating edges, is fixed to a rigid backing plate, and a clamp or anvil prevents the work piece from spreading or lifting during welding. The half-plate where the direction of rotation is the same as that of welding is called the advancing side, with the other side designated as being the retreating side. The rotating welding tool is slowly plunged into the work piece until the shoulder of the welding tool forcibly contacts the upper surface of the material. By keeping the tool rotating and moving it along the seam to be joined, the softened material is literally stirred together forming a weld without melting. The welding tool is then retracted, generally while the spindle continues to turn. After the tool is retracted, the pin of the welding tool leaves a hole in the work piece at the end of the weld. These welds require low energy input and are without the use of filler materials and distortion. FSW involves complex material movement and plastic deformation. Welding parameters, Tool geometry and joint design exert significant effect on the material flow pattern and temperature distribution, thereby influencing the micro structural evolution of material Therefore, welding speed, the tool rotational speed, the tilt angle of the tool, tool material and the tool design are the main independent variables that are used to control the FSW process the main process parameters and there effects in friction stir welding are given below Table 1 (FSW-Technical-Handbook).

Table 1 Main process parameters in friction stir welding.

Parameter	Effects
Rotation speed	Frictional heat, —stirring, oxide layer breaking and mixing of material.
Tilting angle	The appearance of the weld, thinning.
Welding speed	Appearance, heat control.
Down force	Frictional heat, maintaining contact conditions.

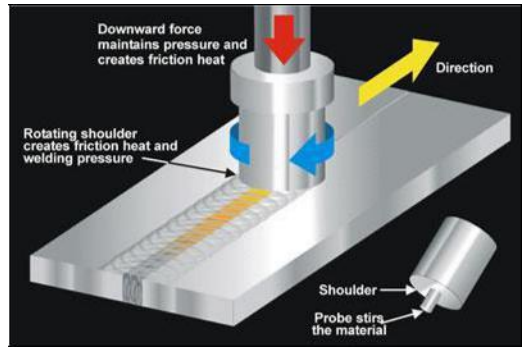


Fig.No.2. Principle of Friction stir welding

B. Tool rotation and Transverse speed

For FSW, two parameters are very important: tool rotation rate (v, rpm) in clockwise or counter clockwise direction and tool traverse speed (n, mm/min) along the line of joint. The motion of the tool generates frictional heat within the work pieces, extruding the softened plasticized material around it and forging the same in place so as to form a solid-state seamless joint. As the tool (rotates and) moves along the butting surfaces, heat is being generated at the shoulder/work-piece and, to a lesser extent, at the pin/work-piece contact surfaces, as a result of the frictional-energy dissipation. The welding speed depends on several factors, such as alloy type, rotational speed, penetration depth, and joint type. Higher tool rotation rates generate higher temperature because of higher friction heating and result in more intense stirring and mixing of material. During traversing, softened material from the leading edge moves to the trailing edge due to the tool rotation and the traverse movement of the tool, and this transferred material, are consolidated in the trailing edge of the tool by the application of an axial force.

C. Tool tilt and Plunge depth

In addition to the tool rotation rate and traverse speed, another important process parameters are tool tilt with respect to the work piece surface and plunge depth. A suitable tilt of the spindle towards trailing direction ensures that the shoulder of the tool holds the stirred material by threaded pin and move material efficiently from the front to the critical issue as its profile influences the stirring of material and quality of the weld to be done. The key of the pin. The tool is usually characterized by a small tilt angle (θ), and as it is inserted into the sheets, the blanks material undergoes to a local backward extrusion process up to the tool shoulder. Further, the plunge depth of pin into the work pieces (also called target depth) is important for producing sound welds with smooth tool shoulders.

D. Tool Design

Tool design influences heat generation, plastic flow, the power required, and the uniformity of the welded joint. Tool geometry such as probe length, probe shape and shoulder size are the key parameters because it would affect the heat generation and the plastic material flow. The tool is an important part of this welding process. It consists of a shoulder and a pin. Pin profile plays a crucial role in material flow and in turn regulates the welding speed of the FSW process. The

shoulder generates most of the heat and prevents the plasticized material from escaping from the work-piece, while both the shoulder and the tool pin affect the material flow. Friction stir welds are characterized by well-defined weld nugget and flow contours, almost spherical in shape, these contours are dependent on the tool design and welding parameters and process conditions used. The commonly used five pin profiles i.e., straight cylindrical, tapered cylindrical, threaded cylindrical, triangular and square pins to fabricate the joints, in FSW are shown schematically in fig.3

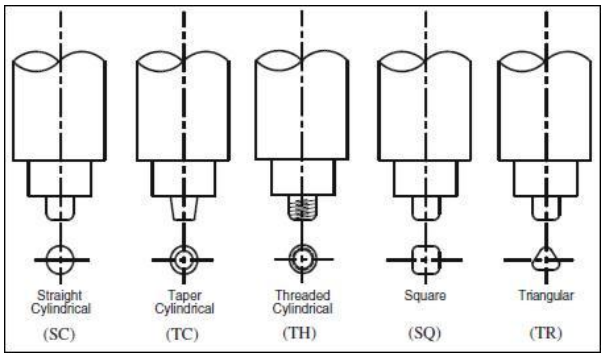


Fig.No.3.Schematic drawing of the FSW tool.

IV EXPERIMENTAL SETUP

A. Material, weld setup and testing procedure

Commercial Al 7075-T651 rolled plates 6.5 mm thick were cut to the required size (100 mm long and 50 mm wide) with the help of power hack saw and milling machine. The tensile testing of the base metal was done on 50 KN computer controlled universal testing machine at room temperature with a constant head speed of 0.5 mm/min. The tested ultimate tensile strength of the base material was found to be 568 MPa. Non consumable tools made from M2 grade high speed steel with a cylindrical threaded pin were used to fabricate the joints. The tools were machined and then subjected to the standard heat treatment cycle for high speed steels to induce an hardness of up to 60 HRC. Close square butt joints were friction stir welded using a conventional vertical milling machine. The welding was done with a specially designed fixture made from SS304.The values of prominent parameters like welding speed and tool travel speed were selected on the basis of optimum values reported in the available literature. A tool tilt angle of 2^0 on the backward side is given to the welding tool. Providing a tilt angle to the tool mainly promotes recoalescence of the material in the stir zone at the rear of the tool. The experiments were carried out with three different shoulder diameter tools. The dimensions of the tools are shown in Figure 4. The process parameters selected for welding are shown in Table 2. During the welding process temperature data were continuously recorded at various locations in the plates using K-type thermocouples. After welding, all the welds were allowed to naturally age for the same period of time. The welds were visually inspected. This was followed by mechanical characterization which consists of tensile testing.

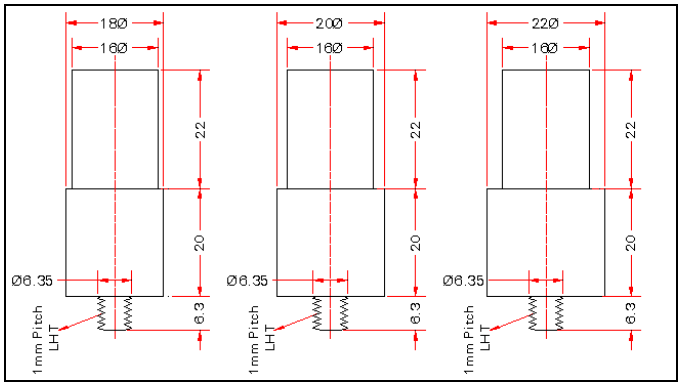


Fig.No.4 .Dimensions of the tool (a) 18mm (b) 20mm (c)22mm shoulder diameter.

Table 2 Process parameter

Sample ID	Shoulder Dia. (mm)	Tool Rotation Speed (rpm)	Welding speed (mm/min)	Tool tilt Angle (degrees)	Tool plunge depth (mm)	Thermo-couples used (nos.)
S1	18	1500	50	2^0	6.5	2
S2	20					2
S3	22					2
S11	18					4
S22	20					4
S33	22					4

B. Thermocouple Layouts

In the experimentation the plates were welded in a single pass and temperature history is recorded during the FSW process by K- type thermocouples having sheath diameter of 1.5mm. Maximum measuring capacity of this type of thermocouple is around 1100 ^{0}C. The analysis for temperature study is carrie out using ENVADA make multi loop scanner with 16 channels. The scanner was connected to a personal computer that contained data acquisition software ESCAN installed for recording temperatures. The temperature histories during FSW are recorded at a time interval of 2 seconds. Two different types of thermocouple layouts are used to measure the temperature distribution in the transverse direction of the weld joint and the thermal histories in the weld direction. The two different types of thermocouple layouts are shown in Figure 5 below.

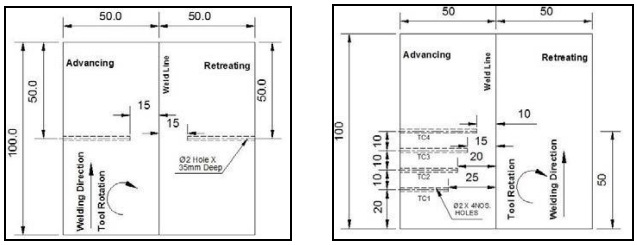


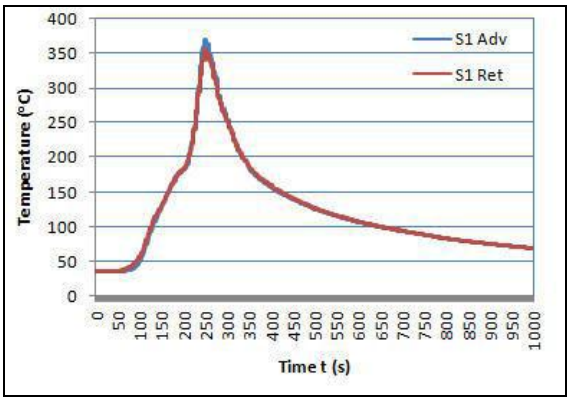
Fig.No.5. Thermocouple Layouts (a) Both sides and equidistance type (b) Same side and unequal distance.

C. Temperature data for both sides and equidistance type layout

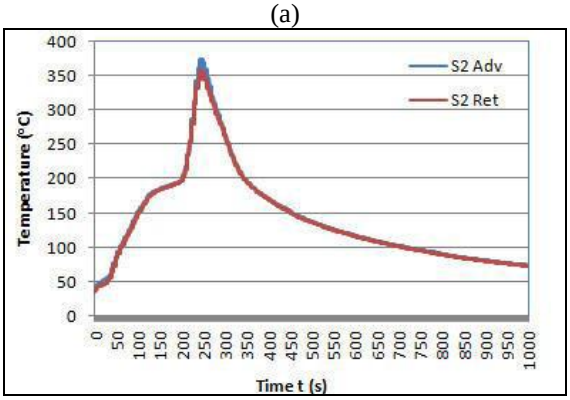
In this type of layout two thermocouples were placed; one on the advancing side and other on the retreating side of the weld joint. Two holes with a diameter of 2mm and depth of 35mm are drilled on both the sides to accommodate the

thermocouples. The distance between the tip of the thermocouple and the weld line is 15mm on each side.

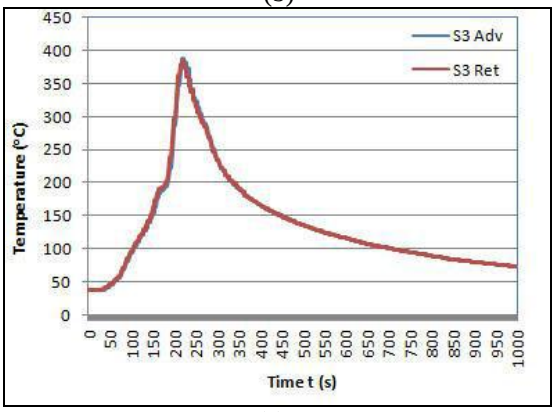
The holes are drilled at the center in the thickness direction of the work piece's side edge side. This type of layout is called "both sides and equidistance type layout" and is mainly used to record the temperature data on the advancing and the retreating sides. This type of layout is shown in Figure 6(a). The temperature data are recorded for three different shoulder diameters tool viz. 18mm (S1), 20mm (S2) and 22mm (S3). Various other FSW parameters were kept constant. The tool rotational speed is 1500 rpm, the welding speed is 50 mm/min and the tool tilt angle is taken as 2^0. The temperature data is recorded for a cycle of 1000 seconds. Figure 6 below shows the temperature profiles recorded for S1, S2 and S3 shoulder diameters on the advancing and the retreating sides.



(a)



(b)



(c)

Fig. No. 6.Temperature profiles on advancing and retreating side (a) S1 (b) S2 (c) S3.

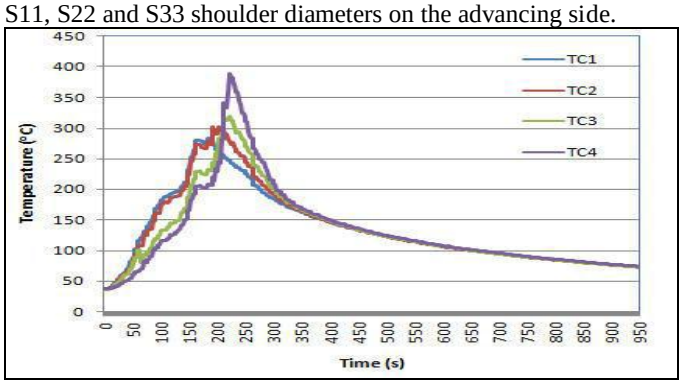
The maximum temperatures recorded on the advancing and the retreating sides for all the three shoulder diameters are shown in table 3 below.

Table 3. Maximum temperatures recorded for both sides and equidistance type layout

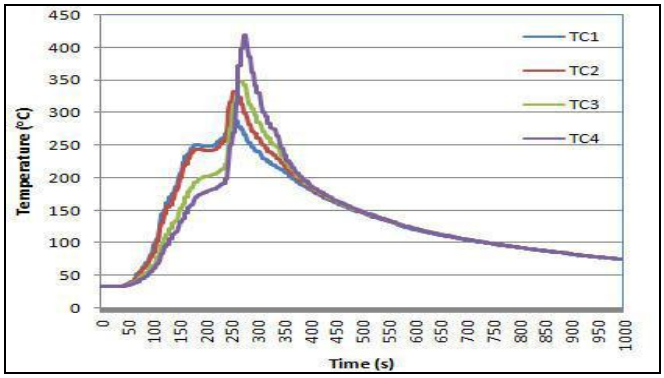
Sample ID	Shoulder Dia.(mm)	Max. Temp.on Advancing side (^{0}C)	Max.Temp.on Retreating Side (^{0}C)
S1	18	370.4	355.3
S2	20	374.4	358
S3	22	387.6	382.7

D. Temperature data for same side and unequal distance type layout

In this type of layout four thermocouples were placed; all on the advancing side weld joint. Four holes with a diameter of 2mm are drilled on the advancing side to accommodate the thermocouples. In this layout the distances from their tips to the weld line are different. The tip of the first thermocouple TC1 is at a distance of 25mm from the weld line. However the distances for the second (TC2), third (TC3) and fourth (TC4) thermocouple tips are 20mm,15mm and 10mm respectively from the weld line. The distances of the thermocouples' tips in the weld direction also vary in the welding direction as shown in Figure 2(b) above. This type of layout is called "same side and unequal distance type layout" and is mainly used to record the temperature data in the transverse direction of the weld joint. The temperature data are recorded for three different shoulder diameters tool viz. 18mm (S11), 20mm (S22) and 22mm(S33). Various other FSW parameters were kept same as the both sides and equidistance type layout. The temperature data is recorded for a cycle of 1000 seconds. Figure 7 below shows the temperature profiles recorded for S11, S22 and S33 shoulder diameters on the advancing side.



(a)



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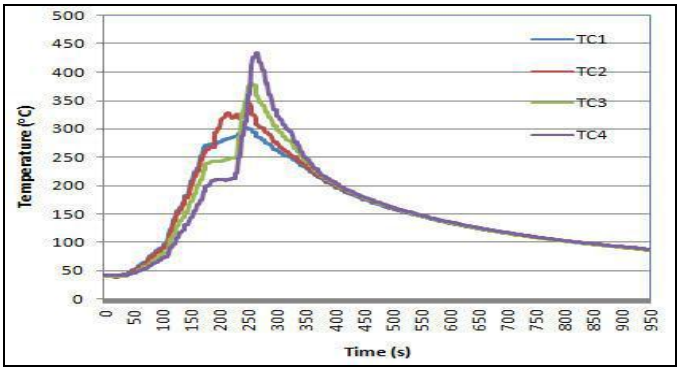

(c)

Fig.No.7. Temperature profiles for same side and unequal distance type layout (a) S11 (b) S22 (c) S33

The maximum temperatures recorded on the advancing side of the same side and unequal distance type layout for all the three shoulder diameters are shown in table 4 below.

Table 4. Maximum temperatures recorded for same side and unequal distance type layout.

Sample ID	Shoulder dia.(mm)	TC1 (°C)	TC2 (°C)	TC3 (°C)	TC4 (°C)
S1	18	283.20	301.78	318.59	389.46
S2	20	290	331.5	347.6	418.4
S3	22	301.2	245.86	380.7	433.80

V MODELING

Modeling is a two-part task, as described in these topics

A. Work piece and tool modeling

B. Contact Modeling

A. Work Piece and tool Modeling:

Two rectangular shaped plates (similar to those used in the reference model) are used as the work piece. Dimensions have been reduced to decrease the simulation time. The plate size is 3 x 1.25 x 0.125 in (76.2 x 31.75 x 3.18 mm). The tool shoulder diameter is 0.6 in (15.24 mm). Plate thickness remains the same as that of the reference model, but the plate length and width are reduced. The plate width is reduced because the regions away from the weld line are not significantly affected by the welding process, and this example focuses primarily on the heat generation and temperature rise in the region nearest the weld line. The height of the tool is equal to the shoulder diameter. A hexahedral mesh with dropped mid side nodes is used because the presence of mid side nodes (or quadratic interpolation functions) can lead to oscillations in the thermal solution, leading to nonphysical temperature distribution. A hexahedral mesh is used instead of a tetrahedral mesh to avoid mesh-orientation dependency. . For more accurate results, a finer mesh is used in the weld-line region. The following figure shows the 3-D meshed model:

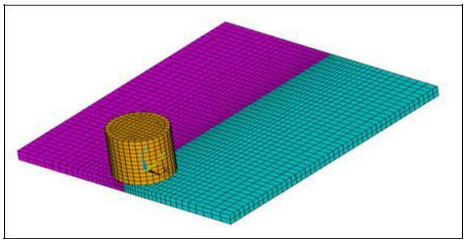

Fig. No.8.D-meshed model of Work piece and Tool

B. Contact Modeling

Contact is modeled as follows for the FSW simulation

1) Contact pair between plates

2) Contact Pair between Tool and work piece

3) Rigid Surface Constraint

VI RESULTS

The results for FSW as follows:

A. Deformation and stresses B. Temperature results

C. Welding results D. Heat generation E. Experimental result

A. Deformation and stresses

It is important to observe the change in various quantities around the weld line during the FSW process. The following figure shows the deflection of the work piece due to plunging of the tool in the first load step

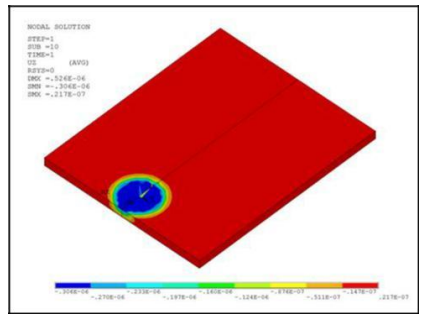

Fig.No.9. Deflection at Work piece After Load Step 1

The deflection causes high stresses to develop on the work Piece beneath the tool, as shown in this figure

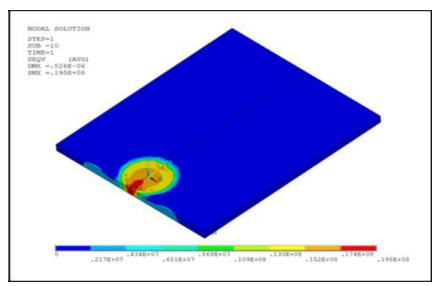

Fig.No.10. Von Mises stress after load step 1

Following load step 1, the temperature remains unchanged (25°C), as shown in this figure:

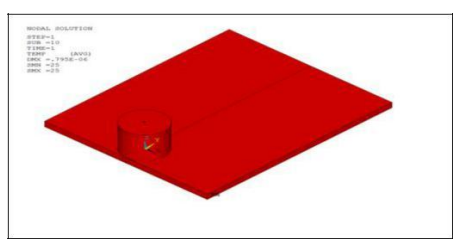

Fig.No.11: Temperature after Load Step 1

As the tool begins to rotate at this location, the frictional stresses develop and increase rapidly. The following two figures show the increment in contact frictional stresses from load step 1 to load step 2.

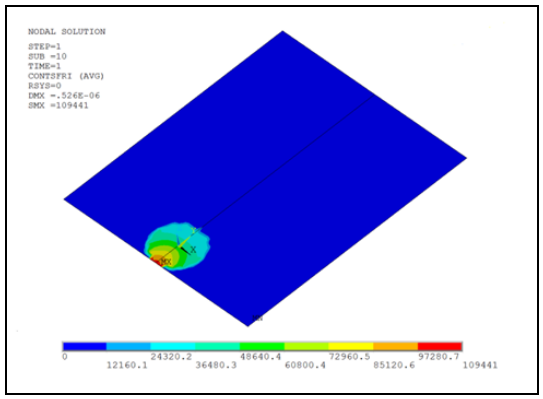

Fig.No. 12 : Frictional Stress after Load Step 1

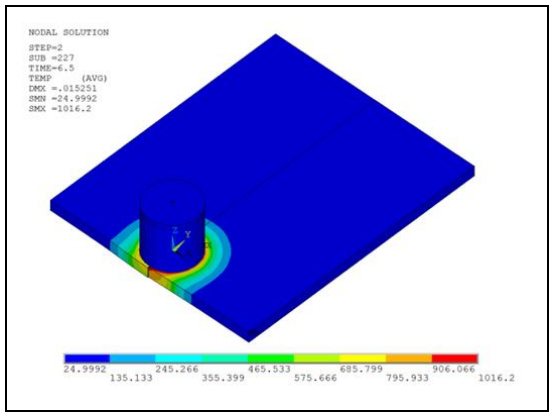

Fig.No.13 : Frictional Stress after Load Step 2

All frictional dissipated energy is converted into heat during load step 2. The heat is generated at the tool- workpiece interface. Most of the heat is transferred to the work piece (FWGT is specified to 0.95). As a result, the temperature of the work piece increases rapidly compared to that of the tool.

B.Temperature Results

The following two figures show the temperature rise due to heat generation in the second and third load steps:

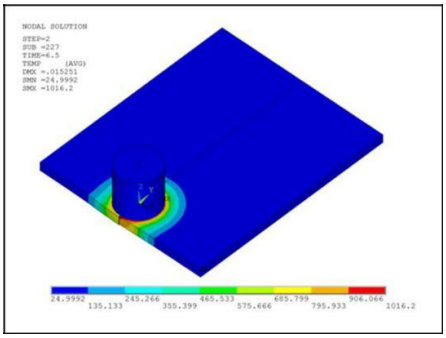

Fig.No.14.Temperature after Load Step 2

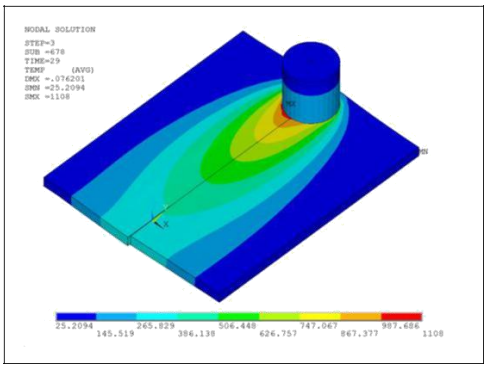

Fig.No.15. Temperature after Load Step 3

The maximum temperature on the work piece occurs beneath the tool during the last two load steps. Heat generation is due to the mechanical loads. No external heat sources are used. As the temperature increases, the material softens and the coefficient of friction decreases. A temperature-dependent coefficient of friction (0.4 to 0.2) helps to prevent the maximum temperature from exceeding the material melting point. The observed temperature rise in the model shows that heat generation during the second and third load steps is due to friction between the tool shoulder and work piece, as well as plastic deformation of the work piece material. The melting temperature of 304L stainless steel is 1450 °C. As shown in the following figure, the maximum temperature range at the weld line region on the work piece beneath the tool is well below the melting temperature of the work piece material during the second and third load steps, but above 70 percent of the melting temperature:

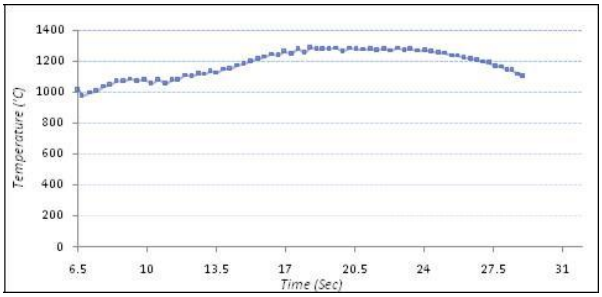

Fig.No.16.Maximum Temperature Variation with Time

The two plates can be welded together within this temperature range. The following figure shows the temperature distributions on the top surface of the work piece along the transverse distance (perpendicular to the weld line)

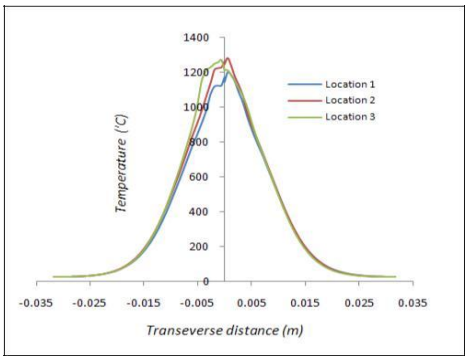

Fig.No.17. Temperature Distribution on the Top Surface of Work piece at Various Locations

C. Welding result

A bonding temperature of 1000 °C is already defined for the welding simulation at the interface of the plates. The contact status at this interface after the last load step is shown in the following figure:

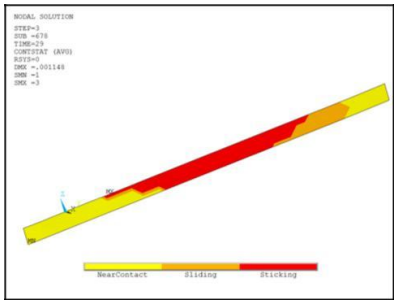

Fig.No.18.Contact Status at Interface with Bonding Temperature 1000 °C

The sticking portion of the interface shows the bonding or welding region of the plates. If the bonding temperature was assumed to be 900 °C, then the welding region would increase, as shown in this figure:

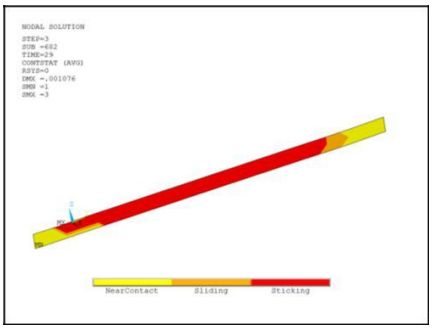

Fig.No.19.Contact Status at Interface with Bonding Temperature 900 °C

D .Heat Generation

Friction and plastic deformation generate heat. A calculation of frictional and plastic heat generation is performed. The generation of heat due to friction begins in the second load step. It is possible to calculate the total frictional heat-generation rate at each time-step. The following figure shows the plot of total frictional heat generation rate on the work piece with time.

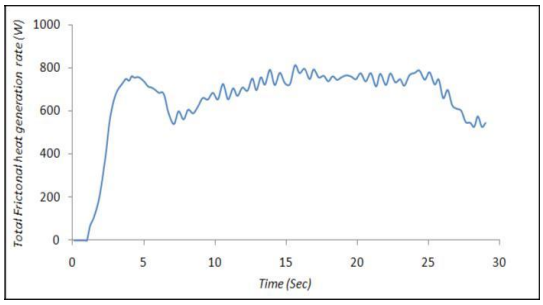

Fig.No.20.Total Frictional Heat Rate Variation with Time

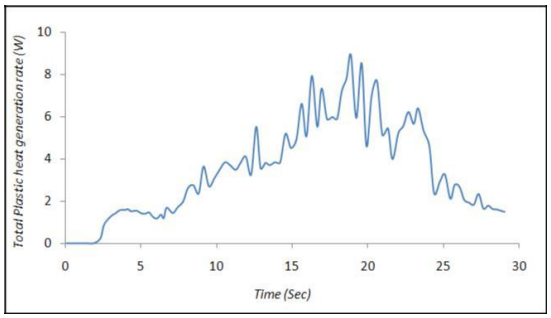

Fig.No.21. Total Plastic Heat Rate Variation with Time

E. Experimental Result

From the experiments performed it is very much evident that the heat generated during the friction stir welding is directly proportional to the tool shoulder diameter. From the both sides and equidistance type layout it is known that the maximum values of temperature recorded on the advancing side are 370.4 ^{0}C, 374.4 ^{o}C and 387.6 ^{o}C for 18mm, 20mm and 22mm shoulder diameters respectively. The temperatures recorded on the retreating side are slightly lesser than compared to the advancing side. They are 355.3 ^{o}C, 358 ^{o}C and 382.7 ^{o}C respectively. The same side and unequal distance type layout indicates that the temperatures increase along the direction of the weld and towards the centre of the weld.

VII CONCLUSIONS

A new heat transfer model used for modeling the heat generation and conduction in FSW is presented in this paper. The real temperature has also been measured in order to validate the modeled results. The following conclusions can draw:

1. This model can be applied in modeling the heat transfer process for friction stir welding.
2. All the chosen parameters have significant influence on temperature evolution during FSW.
3. By increasing the shoulder diameter, plunge depth, and the tool rotation speed, the peak temperature is increased, whereas it is decreasing for increasing welding speed.
4. The shoulder diameter effect is due to increase in higher temperature region.

The temperature distributions in the work piece Al 7075 T651 were determined experimentally during the FSW process. It was observed that the temperatures on the advancing side of the weld are bit higher than that of the retreating side of the weld. Though it is extremely difficult to measure the temperatures at the weld line, an attempt has been made to determine the temperatures around the rim of the tool shoulder. From the study it can be concluded that the appropriate temperature for a defect free friction stir weld of Al 7075 T651 can be within the range of 375 – 420 ^{o}C. The joints fabricated with 20mm shoulder diameter yield maximum joint efficiency. The experimental results obtained can be helpful to control various process parameters during FSW of Al 7075 T651 to achieve defect free, sound and good quality welds.

REFERENCES

[1] Rao, P. *"Microstructure and Mechanical Properties of Friction Stir Lap Welded Aluminum Alloy AA2014"*. Journal of Materials Science & Technology 2011; 28(5): 414–426.

[2] Koilraj, M., Sundareswaran,V., Vijayan, S., & Rao, S. R. K. "*Friction stir welding of dissimilar aluminum alloys AA2219 to AA5083"*-Optimization of process parameters using Taguchi technique Materials Design2012 : 42 :1-7

[3] "*Handbook of Aluminum"*, Alcan Aluminum Corporation ,1970.

[4] AYSYS User's Manual: '*Elements, vol III"*, Swanson Analysis Systems, Inc.

[5]K.Mohanty, M.M.Mahapatra, R Kumar, P.Biswat and N.R.Mandal (April 2012), "*Modeling the Effects of ToolShoulder and Probe Profile Geometries on Friction Stirred Aluminum Welds Using Response Surface Methodology"*, J.Marine Sci., Appl. 11: 493-503

[6]Simar A, Pardoen T, de Meester B (2007*). "Effect of rotational material flow on temperature distribution in friction stir welds."* Sci Tech Weld Join 12(4):324–333. doi:10.1179/17432930

[7]Tang W, Guo X, McClure JC, Murr LE, Nunes A (1998) "*Heat Input and Temperature Distribution in Friction Stir Welding".* J Mater Process Manuf Sci 7:163–172.

[8]Xiaocong He, Fengshou Gu ,Andrew Bal. "*A review of numerical analysis of friction stirsWelding".* Progress in Materials Science 65 (2014) 1–66.

[9] He X, Gu F, Ball A. "*Recent development in finite element analysis of self-piercing riveted joints".* Int J Adv Manuf Technol 2012;58:643–9.

[10]Gemme F, Verreman Y, Dubourg L, Jahazi M." *Numerical analysis of the dwell phase in friction stir welding and comparison with experimental data*." Mater Sci Eng A 2010; 527:4152–60.

[11]C.M. Chen, R. Kovacevic, "*Finite element modeling of friction stir welding-thermal and thermo mechanical analysis",* International Journal of Machine Tools & Manufacture 43, 1319–1326, 2003.

[12] Hamilton C, Dymek S, Sommers A (2008) ."*A thermal model of FSW in aluminum alloys*." Int J Tool &manuf.48(10):1120–1130.doi: 10.1016.

[13]M.A. Sutton, A.P. Reynolds, D.Q. Wang, C.R. Hubbard, "*A study of residual stresses and microstructure in 2024-T3 aluminum friction stir butt welds,"* Journal of Engineering Materials and Technology ASME 124 (4) (2002) 215–221.

[14] M Song, R. Kovacevic, "*Thermal modeling of friction stir welding in a moving coordinate and its validation",* International Journal of Machine Tool and Manufacturing 43 (6) (2003) 605–615.

[15] Polmear IJ. Light Alloys - Metallurgy of light metals. 3rd ed. London: Arnold Publishers; 1995.

[16] Rajakumar S, Muralidharan C, Balasubramanian V. Influence of friction stir welding process and tool parameters on strength properties of AA7075-T6 aluminium alloy joints. Materials & Design 2011;32:535-49.

[17] Feng AH, Chen DL, Ma ZY. Microstructure and Cyclic Deformation Behavior of a Friction-Stir-Welded 7075 Al Alloy.Metallurgical and Materials Transacations A 2010;41:957-71.

[18] Sivaraj P, Kanagarajan D, Balasubramanian V. Effect of post weld heat treatment on tensile properties and microstructure characteristics of friction stir welded armour grade AA7075-T651 aluminum alloy. Defence Technology 2014;10:1-8.

[18] Dieguez T, Burgueño A, Svoboda H. Superplasticity of a Friction Stir Processed 7075-T651 Aluminum Alloy. Procedia Materials Science 2012;1:110-7.

[19] Hatamleh O, Singh PM, Garmestani H. Corrosion susceptibility of peened friction stir welded 7075 aluminum alloy joints. Corrosion Science 2009;51:135-43.

[20] Hatamleh O, Lyons J, Forman R. Laser and shot peening effects on fatigue crack growth in friction stir welded 7075-T7351 aluminum alloy joints. International Journal of Fatigue 2007;29:421-34.

[21] Malard B, De Geuser F, Deschamps A. Microstructure distribution in an AA2050 T34 friction stir weld and its evolution during post-welding heat treatment. Acta Materialia 2015;101:90-100.

[22] Hwang Y-M, Kang Z-W, Chiou Y-C, Hsu H-H. Experimental study on temperature distributions within the workpiece during friction stir welding of aluminum alloys. International Journal of Machine Tools and Manufacture 2008;48:778-87.

[23] Zhang Z, Liu YL, Chen JT. Effect of shoulder size on the temperature rise and the material deformation in friction stir welding. Int J Adv Manuf Technol 2009;45:889-95.

[24] Zhu XK, Chao YJ. Numerical simulation of transient temperature and residual stresses in friction stir welding of 304L stainless steel. Journal of Materials Processing Technology 2004;146:263-72.