International Journal of Emerging Technology and Advanced Engineering
Website: www.ijetae.com (ISSN 2250-2459 (Online), An ISO 9001:2008 Certified Journal,Volume 3, Special Issue 2, January 2013)
National conference on Machine Intelligence Research and Advancement (NCMIRA, 12), INDIA.

Thermomechanical Modeling of FSW: A Review

Deepak Sharma[1], Dr. Rajesh Kumar Bhushan[2]

[1]*School of Mechanical Engineering, Shri Mata Vaishno Devi University, Katra, Jammu and Kashmir, India*
[2]*Assistant Professor, School of Mechanical Engineering, Shri Mata Vaishno Devi University, Katra, Jammu and Kashmir, India*

E-mail: [1]erdeepak786@gmail.com

Abstract

Friction stir welding is gaining significance in typical joining applications day by day. Modeling and simulation of FSW has been a great challenge due to the complexity of the process. We are initiating an effort to review various modeling and simulation techniques mentioned in literature and to find the future scope and possibilities of new techniques.

I. Introduction

Friction Stir Welding (FSW) was invented by Wayne Thomas at TWI (The Welding Institute), and the first patent applications were filed in the UK in December 1991. This process is fast, efficient, capable of producing defect free joints, versatile and environment friendly. FSW is considered to be the most significant development in metal joining and is a ‘‘green’’ technology due to its energy efficiency, environment friendliness, and versatility. As compared to the conventional welding methods, FSW consumes considerably less energy. No cover gas or flux is used, thereby making the process environmentally friendly [1].

Friction Stir Welding is a solid-state process, which means that the objects are joined without reaching melting point. In FSW, a cylindrical shouldered tool with a profiled pin is rotated and plunged into the joint area between two pieces of sheet or plate material. The process of friction stir welding is shown in figure-1. Based on friction heating at the facing surfaces of two sheets to be joined in the FSW process a special tool with a properly designed rotating probe along the contacting metal plates produces a highly plastically deformed zone by the stirring action. The parts have to be securely clamped to prevent the joint faces from being forced apart. Frictional heat between the wear resistant welding tool and the workpieces causes the latter to soften without reaching melting point, allowing the tool to traverse along the weld line.

The plasticized material, transferred to the trailing edge of the tool pin, is forged through intimate contact with the tool shoulder and pin profile. On cooling, a solid phase bond is created between the workpieces. The side on which the tool rotation is parallel to the weld direction is called advancing side and the side on which the tool rotation is opposite to the weld direction is called retreating side.

The FSW process is a solid state process, therefore the problem related to the presence of brittle inter-dendritic and eutectic phases due to solidification structures is eliminated. The low mechanical properties microstructure resulting from melting and resolidification are absent in FSW welds, leading to improved mechanical properties such as ductility and strength alloys with low residual stresses.

The original applications for friction stir welding are the welding of long lengths of material in the aerospace, shipbuilding and railway industries. Examples include large fuel tanks and other containers for space launch vehicles, cargo decks for high speed ferries, and roofs for railway carriages [3].This is because of many of its advantages over the conventional welding techniques some of which include very low distortion, no fumes, porosity or spatter, no consumables (no filler wire), no special surface treatment and no shielding gas requirements. FSW joints have improved mechanical properties and are free from porosity or blowholes compared to conventionally welded materials.

International Journal of Emerging Technology and Advanced Engineering
Website: www.ijetae.com (ISSN 2250-2459 (Online), An ISO 9001:2008 Certified Journal,Volume 3, Special Issue 2, January 2013)
National conference on Machine Intelligence Research and Advancement (NCMIRA, 12), INDIA.

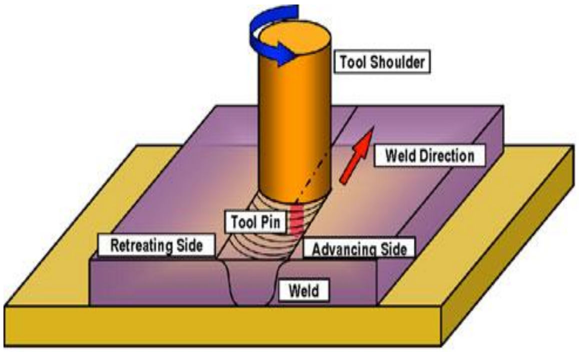

Figure. 1. Process of friction stir welding [13]

II. Microstructural Regions In FSW Welds

The friction stir welded joints possess four mutually distinct microstructural regions as shown in the figure-2. Starting from outside towards the center of the weld, the first region is the un-affected zone i.e. the base metal. No property or microstructural changes occur in this zone. Second region is called heat affected zone or HAZ. A very little microstructural changes used to occur in the HAZ due to the heat of welding but no plastic deformation of base takes place in this zone. The microstructure in this zone consists of coarse grained structure. The third region is thermomechanically affected zone or TMAZ. Although the TMAZ undergoes plastic deformation, recrystallization does not occur in this zone due to insufficient deformation strain but it is affected by the welding heat and considerable microstructural changes takes place in this region. The grain size in this region is found to be finer than HAZ. Fourth region which is plasticized and recrystallized due to the frictional heat produced by the action of rotating pin of FSW tool is called Nugget zone or weld nugget. This region consists of very fine recrystallized equi-axed grains.

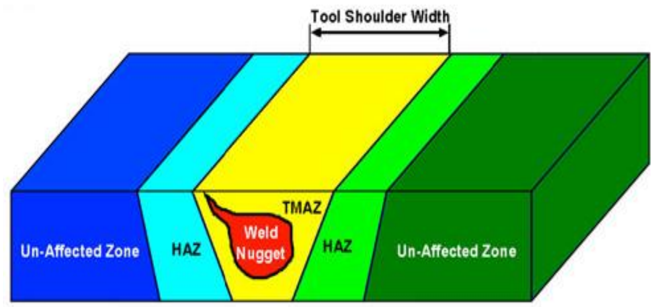

Figure. 2. Various microstructural areas in FSW welds [13]

III. Thermal Models Of FSW

The thermal history of welds plays a vital role in controlling the microstructure evolution in friction stir welds. The mean size and size distribution of the precipitates are very much affected by the thermal cycles during the welding process. The thermal cycles in the process must thus be accurately predicted in order to capture the microstructural evolution in the various zones of the weld and the resulting impact on the weld mechanical properties.

Ref. [2] worked out a thermal modeling of FSW with no mechanical coupling for 6XXX series Aluminium alloys. A pseudo steady state heat transfer problem is solved using the general-purpose finite element code ABAQUS. The model considered the total heat generated as the sum of Heat dissipated by friction at the tool/workpiece interface – surface heat sources and Heat dissipated by plastic deformation - volume heat sources. Material convection around the friction stir welding tool and Contact condition at the workpiece/backing plate interface was also taken into considerations. Figure-3 shows the various heat sources involved in the process of friction stir welding. The governing equations for both heat sources were taken as:

International Journal of Emerging Technology and Advanced Engineering
Website: www.ijetae.com (ISSN 2250-2459 (Online), An ISO 9001:2008 Certified Journal, Volume 3, Special Issue 2, January 2013)
National conference on Machine Intelligence Research and Advancement (NCMIRA, 12), INDIA.

$Q_{s,Shoulder} = \int_0^{2\pi}\int_{ri}^{ro} \tau contact\, \omega r a (1-\delta) r a d\theta d r a$

$QS;pin = \int_0^{2\pi}\int_0^{hp} \tau contact\, \omega r a (1-\delta) r a d\theta a d z$

$QS;pintip = \int_0^{2\pi}\int_0^{ri} \tau contact\, \omega r a (1-\delta) r a d\theta a d r a$ and

$q_v = \zeta\, \acute{\varepsilon}_{ij}\sigma_{ij}$

Where, $\acute{\varepsilon}_{ij}$ and σij are, respectively, the components of the plastic strain rate tensor and the Cauchy stress tensor and ζ is a parameter ranging between 0.8 and 0.99.

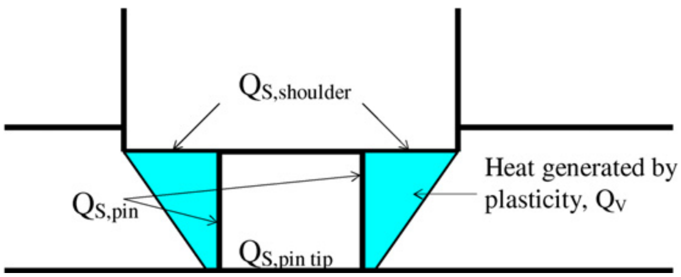

Figure. 3. Schematic of the heat generation by friction at the tool/workpiece interface and by plastic deformation in the TMAZ [2]

Ref. [5] modeled FSW process of AA6061-T6 alloy as a three dimensional problem. The commercial finite element package ANSYS was used as the solver. A typical view of finite elements mesh generation is shown in figure-4. The analytical heat input model has been used for the determination of thermal history and based on which finite element analysis has been carried out and the predicted values were confirmed with experimental measurement data. From the experimental and Numerical analysis, it has been clearly observed in FSW weldment that the retreating side temperature distribution was found to be relatively higher than the advancing side.

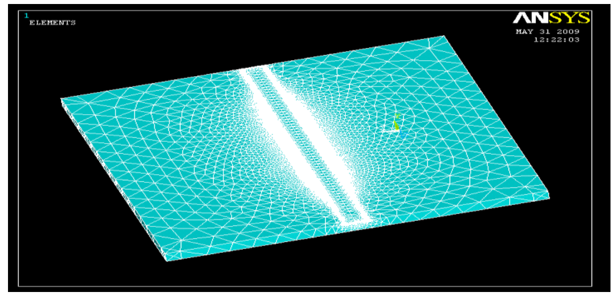

Figure. 4. A view of Finite Element mesh [5]

Ref. [8] simulated the FSW process successfully using the Finite Element code, DEFORM. The tool (the probe and pin shoulder) was modeled as a rigid body, while the plate (the workpiece in shape of a plate) was modeled as a plastic body. The model of meshes generated for study is presented in figure-5. The different types of meshes and nodes for FSW tool and the workpiece are clearly identifiable. It was observed that temperature gradients are higher toward the leading edge than toward the trailing edge, temperatures were found to be higher near the interface between the shoulder and the plate. It was also to be observed that the temperatures are widely distributed toward the retreating side of the tool than on the advancing side.

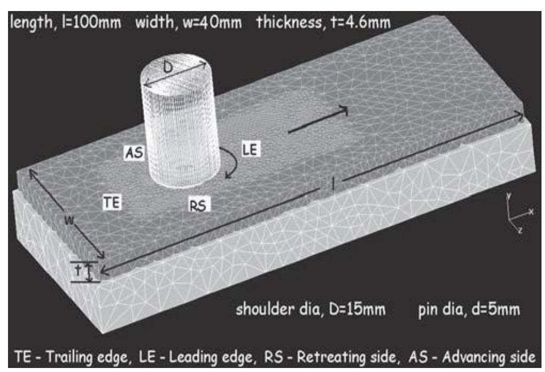

Figure. 5. Setup of FSW for numerical simulations [8]

International Journal of Emerging Technology and Advanced Engineering
Website: www.ijetae.com (ISSN 2250-2459 (Online), An ISO 9001:2008 Certified Journal,Volume 3, Special Issue 2, January 2013)
National conference on Machine Intelligence Research and Advancement (NCMIRA, 12), INDIA.

Ref. [9] conducted a virtual experiment with three dimensional nonlinear thermal numerical FE simulation using Altair's Hyperweld FSW software module. The temperature at different positions from the center of the tool was possible to predict. It was further concluded that with this package one can easily note the temperature at any section of the weld zone or at any node point which is not possible during the actual process.

IV. Mechanical Models Of FSW

Ref. [2] suggested the strain hardening model for pure metals in relation to the taylor relation as:

$d\sigma_y/d\varepsilon_p = \theta_0 - \beta_0(\sigma_y\text{-}\sigma_0)$

Where, $\theta_0 = \alpha GbM_2k_1/2$ and $\beta_0 = k_2M/2$

The strain hardening model was suggested to be governed by the following equation:

$d\rho/d\gamma_p = k_1\sqrt{\rho}+(1/bl)\text{-}k_2\rho$

Where, ρ is dislocation density and γ_p is plastic shear strain.

Ref. [4] studied the simulation of superplastic forming by ABAQUS and stated the dependency of the flow stress upon the strain-rate, which allows the material to be described as rigidviscoplatic. The equivalent strain-rate was obtained from the equation:

$$\sigma = K\acute{\varepsilon}^m$$

Linear quadrilateral elements were used to model the deformable body and linear triangular elements were used to model the rigid body. A large number of nodes and elements have been used for analysis of hemispherical dome shape and concluded that the fine meshed area bulge profile increased during the forming with consequent decrease in thickness at the pole. Ref. [7] developed model to simulate mechanical response of FSW and SPFFSW joints using the commercial FEA Modeling software ANSYS V.10 and compared the results to experimentally determined behavior characteristics to assess the validity of the modeling approach.

A strong correlation between numerical and experimental results was observed in FSW simulation and SPF-FSW simulation results showed a discrepancy in elastic region. The elastic modulus predicted by the model was reported to be lower than the experimentally determined modulus. The stress and strain at yield predicted by the model showed a decrease in strength and an increase in elongation compared to the experimental results. Ref. [8] analyzed the distributions of temperature, residual stress, strain, and strain rates using finite element (FE) code DEFORM. The intensity of the effective stresses was found to be comparatively low at the advancing side than toward the retreating side while no significant difference in the same was observed between trailing edge and leading edge and between top and bottom surface of the plates. The effective strains were found to be somewhat higher and more widely distributed toward the retreating side of the pin than toward the advancing side of the pin.
Ref. [12] in the study of FSW of AA2219 aluminium alloy; developed an empirical relation between the tensile strength as a response function and the welding parameters as:

$$TS = f\,(P, N, S, F)$$

The second-order polynomial (regression) equation was used to represent the response surface Y as:

$$Y = b_0 + \Sigma b_i x_i + \Sigma b_{ii} x_i + \Sigma b_{ij} x_i x_j$$

The results was carried out successfully using design of experiments, ANOVA and regression analysis.

V. Thermomechanical Models Of FSW

Ref. [6] suggested a fully coupled thermomechanical model for simulation of FSW of AA2524 aluminium alloy with ABAQUS. The flow equation used in this study was given as:

$$c_\varepsilon - c_\lambda(\partial g/\partial\sigma) - \Delta\lambda[(\partial^2 g/\partial\sigma\partial\sigma):c_\sigma + (\partial^2 g/\partial\sigma\partial H_\alpha)c_\alpha] = \Delta\lambda(\partial g/\partial\sigma) - \partial\varepsilon^{pl}$$

International Journal of Emerging Technology and Advanced Engineering
Website: www.ijetae.com (ISSN 2250-2459 (Online), An ISO 9001:2008 Certified Journal, Volume 3, Special Issue 2, January 2013)
National conference on Machine Intelligence Research and Advancement (NCMIRA, 12), INDIA.

The Newton–Raphson iteration method was applied until the flow equation and yield constraints are satisfied. Ref. [10] reported the strains and strain rates during FSW of AA2524 from a three-dimensional coupled viscoplastic flow and heat transfer model. The strain tensor was computed by the equation:

$$\varepsilon_{ij} = \sum_{k=1}^{N-1} 1/2[\left(\frac{\partial ui}{\partial xj} + \frac{\partial uj}{\partial xi}\right)^k \times (\Delta x_s/u_s)^k$$

Ref. [11] stated that the numerical welding simulation requires a wide range of material properties as input data. Considering the temperature field calculation, the thermophysical properties i.e. density, specific heat capacity and thermal conductivity λ are needed. For the calculation of the distortions and stresses, the thermomechanical properties i.e. yield strength, hardening behavior, Young's modulus, thermal expansion and Poisson's ratio are a prerequisite. Calculation of the thermal conductivity as input for the simulation has been suggested by the equation:

$$\lambda(T) = a(T).\ \rho(T).\ c_p(T)$$

The tensile strain calculation has been suggested using thermal expansion coefficient at room temperature as:

$$\varepsilon = \alpha_{RT}(\Delta T/\Delta t)$$

The combined effect of the temperature and strain rate on the yield strength can be checked in accordance with equation:

$$\sigma_y(T)/\sigma_{y,0}(T) = \left(\frac{\varepsilon}{\varepsilon 0}\right)^{m(T)}$$

Ref. [13] analyzed The FSW process computationally using a fully coupled thermo-mechanical finite-element algorithm within which heat dissipation associated with plastic deformation and tool/work-piece interfacial friction-sliding is treated as a source in the governing thermal equation while the effect of temperature on the mechanical response of the work-piece material is taken into account through the use of a temperature-dependent work-piece material model.

During the FSW process simulation, the material is prevented from flowing through the bottom face of the work-piece computational domain; standard convective boundary conditions are applied over free surfaces of the work-piece and the tool while enhanced convection boundary conditions are applied over the bottom face of the work-piece

Work-piece/tool interactions are accounted for through the use of a penalty algorithm within which the extent of contact pressure is governed by the local surface penetrations while shear stresses are transferred via a ''slip/stick'' algorithm, that is shear stresses lower than the frictional shear stress are transferred without interface sliding. The frictional shear stress is defined by a modified Coulomb law within which there is an upper limit to this quantity. An Arbitrary Lagrangian-Eulerian (ALE) formulation was used within which adaptive re-meshing is carried out to maintain good quality mesh. The fully coupled thermo-mechanical problem dealing with FSW was solved using an explicit solution algorithm implemented in ABAQUS/Explicit

VI. SUMMARY

Simulation and modeling of friction stir welding is a quite difficult task due to the complexity of the process. Several simulation software packages and various thermal, mechanical and thermomechanical models of FSW have been discussed in this review which were found to be efficient in the simulation of the process. FEM, ANSYS, ABAQUS and DEFORM are found to be frequently used and quite effective in the successful simulation and analysis of various aspects of FSW process like temperature distribution, stress and strain associated, strain hardening and superplastic forming.

Since, there is a scarcity of literature on simulation and modeling of FSW; possibilities of using some new techniques may be explored. Further, most of the literature available is concerned with FSW of metals and alloys, the evidences of simulation of FSW for metal matrix composites (MMC) are lacking in literature. Therefore, the research is needed for thermomechanical modeling of FSW process specifically for metal matrix composites.

International Journal of Emerging Technology and Advanced Engineering

Website: www.ijetae.com (ISSN 2250-2459 (Online), An ISO 9001:2008 Certified Journal, Volume 3, Special Issue 2, January 2013)

National conference on Machine Intelligence Research and Advancement (NCMIRA, 12), INDIA.

REFERENCES

[1] R.S. Mishra and Z.Y. Ma, "Friction stir welding and processing," Materials Science and Engineering, vol. R 50, pp. 1–78, 2005.

[2] A. Simar et al., "Integrated modeling of friction stir welding of 6xxx series Al alloys: Process, microstructure and properties," Progress in Materials Science 57, pp. 95–183, 2012.

[3] Richard Johnson and Stephan Kallee, "Friction Stir Welding," Materials World, Vol. 7 no. 12, pp. 751-53, December 1999.

[4] P.Ganesh and V.S. Senthil Kumar, "Finite element simulation in superplastic forming of friction stir welded aluminium alloy 6061-T6," International Journal of Integrated Engineering, Vol. 3 No. 1 (2011) p. 9-16.

[5] Selvamani S.T, Umanath K and Palanikumar K, "Heat Transfer analysis during friction stir welding of Al6061-T6 alloy," International Journal of Engineering Research and Applications (IJERA), Vol. 1, Issue 4, pp. 1453-1460.

[6] Z. Zhang & H. W. Zhang, "A fully coupled thermo-mechanical model of friction stir welding," Int. J. Adv. Manuf. Technol., vol. 37,pp. 279–293, 2008.

[7] Paul D. Edwards, Daniel G. Sanders, and M. Ramulu, "Simulation of Tensile Behavior in Friction Stir Welded and Superplastically Formed-Titanium 6Al-4V alloy," ," JMEPEG, vol. 19, pp. 510–514, 2010.

[8] K. Uyyuru and Satish V. Kailas, "Numerical Analysis of Friction Stir Welding Process," JMEPEG, vol. 15, pp. 505-518, 2006.

[9] Sandeep Patil, Sachin Lomte and Dr. CL Gogte, "Thermal analysis of friction stir welded joint of age hardenable AA7075 using Altair's hyperweld FSW," HTC 2012, pp. 1-6

[10] A. Arora, Z. Zhang, A. De and T. DebRoy, "Strains and strain rates during friction stir welding," Scripta Materialia, vol. 61, pp. 863–866, 2009.

[11] C. Schwenk AND M. Rethmeier, "Material properties for welding simulation—measurement, analysis, and exemplary data," Welding Journal, Vol. 90, pp. 220s-227s, 2011.

[12] K. Elangovan, V. Balasubramanian, and S. Babu, "Developing an empirical relationship to predict tensile strength of friction stir welded AA2219 Aluminum Alloy," JMEPEG, vol. 17, pp. 820-830, 2008.

[13] M. Grujicic, G. Arakere, C.-F. Yen, and B.A. Cheeseman, "Computational Investigation of Hardness Evolution During Friction-Stir Welding of AA5083 and AA2139 Aluminum Alloys," JMEPG, Published online 2010.