International Journal of Research in Advent Technology, Special Issue, December 2018
International Conference on Mechanical and Civil Engineering (ICOMACE-2018)
E-ISSN: 2321-9637
Available online at www.ijrat.org

Evaluation of Residual Stresses in Friction Stir Welded AA 5059 Aluminium Alloy Joints Using Comsol Software

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Abstract: Friction stir welding (FSW) is a solid state welding process, which, is a comprehensive method for joining nonferrous materials such as aluminium alloys. However, physics involved in FSW is complex, nonlinear mutiphysical phenomena. It is hard for any experimental technique to predict the complete mapping of residual stress and temperature field involved during FSW. In FSW a momentous residual stress is present in the weld due to complex nature of fixturing system compared to that of fusion welding. Residual stress causes buckling or brittle fractures in welded structures. So the estimation of residual stress is required to protect the structures. The objective of the present paper is to analyse the geometrical distribution of residual stresses arising in 4mm thick AA 5059 Aluminium plates due to FSW process by means of finite element analysis using COMSOL software. Further residual stresses were measured by means of X-ray diffraction method. The numerical values obtained by finite element analysis are found to be in close agreement with experimental values.

Keywords: Friction Stir Welding, Residual stress, Aluminium alloy, Finite element analysis.

1. INTRODUCTION

Welding is used to join materials into parts and parts into structures and assemblies. The interest in the use of aluminum as a structural material in industrial applications has increased greatly in recent years. This increase is primarily due to the low weight of aluminium compared to other structural materials as well as its ability to resist corrosion. Since welding is a localized application of heat, uneven distribution of temperature is prevailed along the weld joint. This induces uneven stress patterns in the weld joints [1]. In general, due to its high thermal conductivity and low melting temperature, aluminium is extremely susceptible to deformations associated with high temperatures. Larger temperature gradient, thermal expansion coefficient and temperature distribution through the material affect the distribution of residual stress [2]. The uneven distribution of residual stress results in contraction and expansion of the weld joint. Thus on service condition, the residual stress and distortion results in the poor performance of the weld joint.

In this research work, the non-heat treatable alloy AA 5059 H-136 is taken for investigation. This alloy is produced at Koblenz,Germany,byAleris International ,Inc . [3] .Nowadays, aluminium alloys are used in many applications in which the combination of high strength and low weight is attractive. Shipbuilding is one area in which the low weight can be of significant value. The AA 5059 is the most frequently used aluminium alloy in shipbuilding industries as a hull material due to its high corrosion resistance. As a result, 5000 series of aluminium alloys find wide application in building and construction, highway structures, including bridges, storage tanks and pressure vessels, cryogenic tanks and systems for temperature as low as -270°C and marine applications[4].

In this study X-ray diffraction technique is used for stress measurements. 5-6]. T his method is one of the widely used non-destructive techniques for residual stress measurements. Finite element methods have also been used to calculate residual stresses [9]. Moreover, the use of the finite element method (FEM), one of the most commonly applied numerical approaches in simulating welding processes, is dramatically increased. Thus, FE models that facilitate the parametric study of available residual stresses are necessary. Applying FEM modeling to predict thermal history and residual stress has become a fairly common practice at present.

Though the heat supplied by FSW process is lower than that of fusion welding processes, it is still a process accompanied with uneven heating and cooling. So the presence of residual stress and distortion is inevitable. Residual stress plays a vital role in determining the strength of the hull structure in a ship building industry. Hence, a systematic investigation was planned in this work is to evaluate residual stress by conducting experiments and develop a model and validate between these two.

2. EXPERIMENTAL PROCEDURE

The chemical composition of the parent metal is evaluated by vacuum spectrometer (ARL model 3460). Sparks were ignited at various locations, and their spectrum was analyzed and the estimated alloying elements are presented in Table 1. The parent metal mechanical properties are shown in Table 2. The parent metal was prepared into sizes of 150 × 75

× 4 mm for welding. Photograph of Friction Stir Welding machine utilized in this investigation is

Shown in Fig.1.

Fig1: FSW machine used for fabricating the joints

Trial experiments were conducted to attain defect free joint and those combination of parameters were considered as optimized parameters. The optimized process parameters and tool parameters used in this investigation are presented in Table 3. The fabricated joints are shown in Fig.2. In this study, AST 3000 X-ray stress analyzer employing CrKα radiation (at DMRL, Hyderabad, India) was used for residual stress measurements. The residual stress was measured in one specimen at the weld centre and at 7mm and 12 mm away from the weld centre. The measured strains are then converted into a stresses through Hooke's Law [2,4]. X-ray diffraction method employs Bragg's law to estimate the residual strains present in the atomic plans.

Table 1 Chemical composition (wt. %) of base material

Si	Cu	Mn	Mg	Cr	Zn	Ti	Al
0.04	0.003	0.933	5.21	0.5-0.6	<0.001	0.489	Remain.

Table 2 Mechanical properties of base material

Ultimate tensile strength (MPa)	0.2% Yield strength(MPa)	Elongation in 50mmgauge length (%)	Hardness(HV 0.05 kg@ 15 sec)
385	290	16	123

Table 3 Welding Conditions and process parameters used in this investigation

Parameters	FSW process
Welding machine	RV Machine tools, India.
Welding speed (mm/min)	25
Rotational speed (rpm)	950
Axial force (kN)	3.4
Tool pin profile	Taper Threaded
Shoulder diameter(mm)	12
Pin diameter(mm)	4
Pin length(mm)	3.7
Tool tilt angle(Degree)	2.5

A selection of "d vs. $\sin^2\psi$" stress measurement process was made in order to get accuracy and precision. Bragg's Law defines the relationship among the wavelength (λ), diffracted beam angle (2 and the interplaner spacing of the lattice (d)

(1)

$$n\lambda = 2dz$$

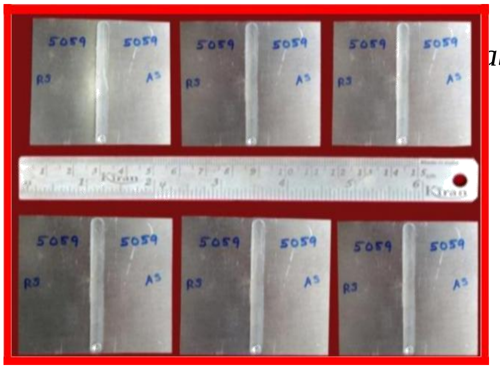

Fig2: Photograph showing fabricated joints

3.0 NUMERICAL ANALYSIS

In this analysis, COMSOL software was used to predict the temperature distribution and residual stress in friction stir welded AA 5059 aluminium alloy joints. For the modeling of residual stress in welds, an advantage will be the ability to couple physics from solid mechanics and heat transfer relationships [13].

Calculation of the residual stress in FSW due to thermal gradient induced strains, strains caused by micro structural changes and strains due to mechanical loading requires thermo elasto-plastic formulations. In the stress analysis, the temperature history obtained from the thermal analysis is taken as input for determining thermal strains and stresses. Thermal strains and stresses are calculated in addition to the mechanical strains and stresses due to the axial load of the tool and the cumulative stresses are found at each load step. Before the next temperature increment, these stresses are then added to those at nodal points to update the behaviour of the model.

The constitutive laws relating stresses, strains, and temperature are nonlinear in the theory of plastic deformation of solids. Two basic sets of equations relating to the elasto-plastic model, the equilibrium equations and the constitutive equations are considered [10]. One is equation of equilibrium (in Cartesian co-ordinates) another one is constitutive equations for an elasto-plastic material. For an isotropic material, there are only two independent elastic constants K and G, known as Lame's constants and the generalized Hook's Law gives the stress –strain relations.

The following equations were used in the thermal model analysis

$$-\left(\frac{\partial Rx}{\partial x}+\frac{\partial Ry}{\partial y}+\frac{\partial Rz}{\partial z}\right)+Q(x,y,z,t)=\rho C\frac{\partial T(x,y,z,t)}{\partial t} \quad .$$

(2) where *Rx*, *Ry*, *Rz* are the rates of heat flow per unit area, *T*(*x*, *y*, *z*,*t*) is the current temperature, *Q*(*x*, *y*, *z*, *t*) is the rate of internal heat generation,

is the density, *C* is the specific heat and *t* is the time. The model is completed by introducing the Fourier heat flow as:

Rx = -Kx

(3)

Ry = -Ky

(4)

Rz = -Kz

(5) where *Kx*, *Ky*, *Kz* are the thermal conductivities in the *x*, *y* and *z* directions, respectively.

The differential equations governing heat conduction in a solid body can be written as:

$$\frac{\partial}{\partial x}\left(Kx\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(Ky\frac{\partial T}{\partial y}\right)+\frac{\partial}{\partial z}\left(Kz\frac{\partial T}{\partial z}\right)+Q=\rho C\frac{\partial T}{\partial t}$$

(6)

In the mechanical analysis, the temperature histories obtained from the thermal analysis were input as thermal loadings into the structural model. The final states of residual stresses were obtained by totaling the thermal and mechanical strains and stresses. The materials were assumed to be isotropic and the linear strain hardening behavior was used. The von-mises yield criterion was employed. The elastic modulus and yield stress of the material were considered temperature dependents. During the welding process, the total strain rate can be decomposed into three components as follows:

$$\epsilon_{total}=\epsilon_e+\epsilon_p+\epsilon_{th}$$

(7) $_{total}$ is the total strain produced, $_e$ is the elastic strain, $_p$ is the plastic strain and $_{th}$ is the thermal strain. The elastic strain is modeled using the isotropic Hooke's law with temperature dependant Young's modulus and Poisson's ratio. The thermal strain is computed using the temperature dependent coefficient of thermal expansion. Kinematic hardening is taken into account as an important feature because material

points typically undergo both loading and unloading in the course of the welding process. In this mechanical analysis, the temperature histories obtained from the thermal analysis were given as input as thermal loadings into the structural model. The thermal strains and stresses were calculated at each time increment. The final states of residual stresses were obtained by totaling the thermal and mechanical strains and stresses.

4 RESULTS AND DISCUSSION

4.1 Temperature Measurement

The thermo-mechanical non linear simulation of welding process is modeled and analyzed. The thermal gradient of higher temperature to lower temperature and their distribution from weld centre in transverse direction were clearly observed by the difference in color contour. Due to high thermal conductivity, the heat generated at the weld centre due to welding is readily transferred to the next region. Because of this, the differences in temperature with respect to distance changes at every instance as the weld ramp proceeds. Figure 3 shows the predicted temperature distribution numerically for the optimized process parameters. As shown in the figure, the maximum temperature was found at the centre of the top surface, reaching 712.2 kelvin that is just below the solidus temperature of AA 5059. The numerically predicted peak temperature is within the generally accepted temperature range in the stir zone of the weld. The maximum temperature was 712.2 kelvin which is 82.71% of melting temperature of the material (861kelvin) which was observed at the stir zone due to the stirring action of the rotating pin and forging action of the shoulder.

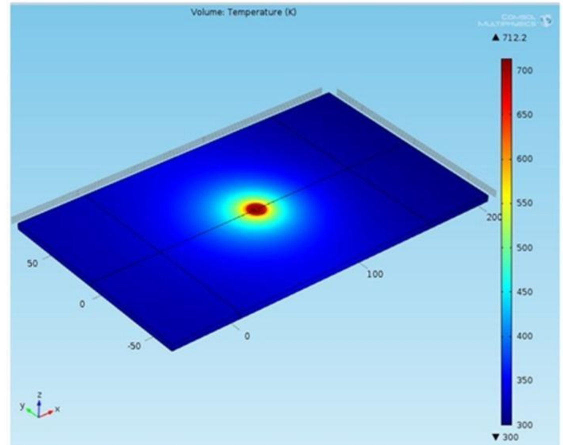

Fig3: Predicted temperature field (in K)

4.2. Residual Stress Measurement

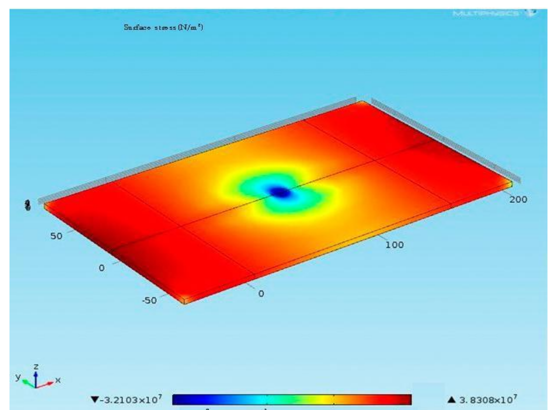

Fig4: Transverse residual stress distribution of FSW joint

Figure 4 shows the transverse stress field of FSW joint. The transverse stress field shows that a compressive stress is formed at the weld centre, where as a tensile stress appears at the back of it, mainly due to the restriction of the material thermal expansion. A compressive stress field is formed near the high temperature region, whereas a tensile stress is formed at the relatively low temperature region. As time progresses the temperature in the hot weld zone decreases; whereas temperatures in the surrounding cold region start to increase due to heat conduction from weld zone. This causes the metal close to weld zone begin to contract, whereas in the surrounding region the metal expands [12,14,15]. Hence a gradually increasing tensile stress is formed when time progresses and a maximum compressive stress of 32 MPa was predicted at the weld bead. Further, the compressive stress reduces with the increase in distance from the

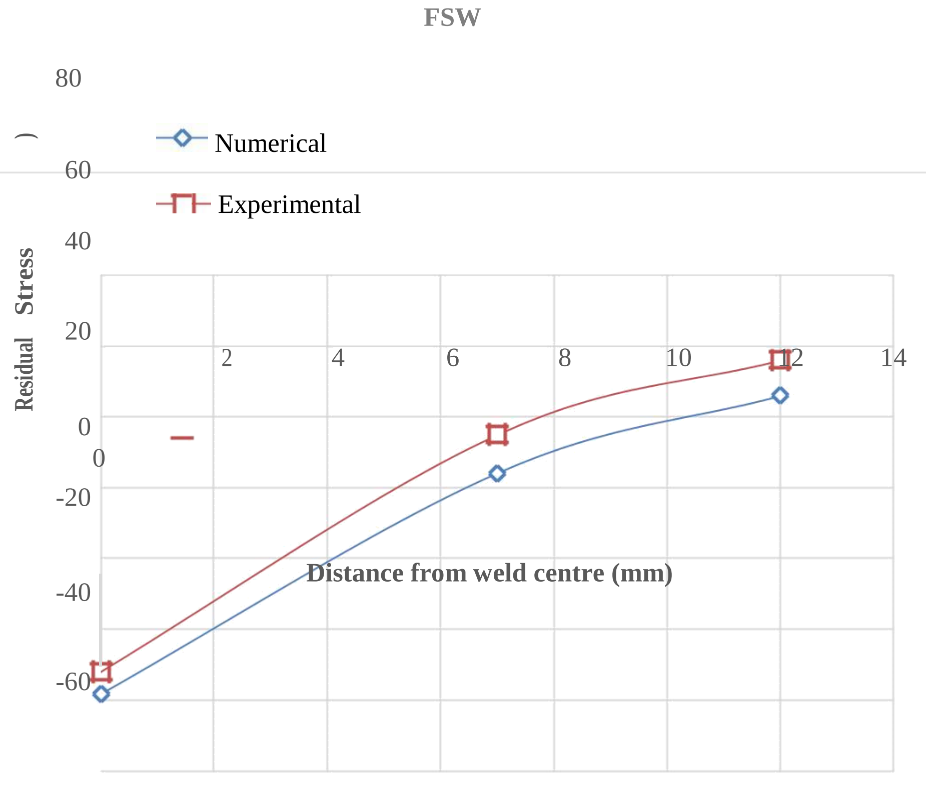

Fig5: Transverse Residual Stress (Experimental Vs Numerical)

At Weld centre		7 mm from weld centre		12 mm from weld centre	
Experimental	FEA	Experimental	FEA	Experimental	FEA
`-38.4	-32	25.3	20	46	38

Table 4 Measured and Predicted Residual stress (MPa) Values

weld zone and reaches tensile stress 38 MPa at the edge of the plate. This trend is similar to that of the results published. Table 4 lists the comparative values of residual stress distribution obtained from experimental and FEA of AA 5059 aluminium alloy.

5 CONCLUSIONS

Some of the important conclusions derived from this investigation are listed below:

(i) . The predicted values of temperature using the non linear three dimensional FEA model are in good agreement with the experimental values. Peak temperature of 712.2 kelvin was predicted at the stir zone. When the distance increases from the centre of the weld, temperature decreases gradually.

2. Due to stirring action of the rotating pin and forging action of the shoulder, the stir zone is under compressive residual stress field (-38 MPa) and away from the stir zone, tensile residual stress field prevails in the FSW joint.

REFERENCES

[1] Aluminum Alloy, Materials Science and Engineering A, Vol. 456 2006 pp. 344-349.

[2] Noyan I. C. and Cohen J. B., Residual Stress Measurement by Diffraction and Interpretation 1987, Springer-Verlag New York Inc.: Germany

[3] Anderson.T., "New developments within the Aluminium Shipbuilding Industry", 2003, 58, 3-5.

[4] Matrinez S. A. and Sathish S., "Residual stress distribution on surface-treated Ti-6Al-4V by x ray diffraction," Society for Experimental Mechanics, 2003, 43(2) 141.

[5] Hatamleh O., "A comprehensive investigation on the effects of laser and shot peening on fatigue crack growth in friction stir welded AA 2195 joints," International Journal of Fatigue, 2009, 31 974.

[6] Prevey P. S., "X-ray Diffraction Residual

[7] Stress Techniques," Metals Handbook, 9th Edition, Vol. 10, American Society for Metals, Metals Park, OH 1986, 380.

[8] Cullity B. D., "Elements of X-ray Diffraction" 1978, Addison-Wesley Publishing Company, Inc.: Reading, Massachusetts.

[9] Dolle H. and Cohen J. B., "Evaluatio n of (residual) stresses in textured cubic metals," m*etallurgical Transactions A*, 1980, 11A, 831.

[10] Brakman C. M. and Penning , "Non- linear diffraction strain Vs $\sin^{2\varphi}$ phenomena in specimens exhibiting rolling-type texture," Acta Crystallographica, 1988, A44, 163.

[11] Chang P.H. and Teng T.L., "Numerical and experimental investigations on residual stresses of the butt welded joints", Computational Material Sciences', 2004, 29, 511-522.

[12] Tang W., Guo X., McClure J. C. and Nunes A. C., " Heat Input and Temperature Distribution in Friction Stir Welding, Journal of Materials Processing and Manufacturing Science, 1998, 7(2), 163-172.

[13] Buffa G., Ducato A. and Fratini L.," Numerical procedure for residual stresses prediction in friction stir welding," Finite Elements in Analysis and Design, 2011, 47, 470–476.

[14] Chang P.H. and Teng T.L., "Numerical and experimental investigations on residual stresses of the butt welded joints", Computational Material Sciences', 2004, 29, 511-522.

[15] Comsol 2006. www.comsol.com.

[16] Gonsalves C.V., Vilarinho L.O., Scotti G. and Gulmaraes G., " Estimation of heat source and thermal efficiency in GTAW process by using inverse techniques", Journal of Materials Processing Technology, 2006, 172, , 42-