EXPERIMENTAL AND ANALYTICAL INVESTIGATION OF FRICTION STIR WELDING OF ALUMINIUM ALLOYS

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Abstract Friction stir welding is a relatively new welding technology originally developed for welding of aluminium and its alloys. The process utilizes a rotating pin-like tool that is plunged into the material to be welded and traversed through the direction of the weld. The overall effect is an in-situ solid extrusion process in which the metal is plasticized by the frictional heating of the tool-motion and forms a very high quality welded joint as the tool passes through it. Shipbuilding industry is one of the first to take advantage of the technique, while aerospace industry and automobile industry are also leaning towards this technique that offers the tremendous possibility of making rivet-free joints that are nearly as good as the parent metal.Material microstructure in and around the weld nugget has been widely studied especially for different Aluminium alloys while the thermal profile during the welding process is still being investigated in order to better understand the different factors affecting the material properties in the weld nugget and the heat-affected zone. Besides experimentations, modelling efforts have also been dedicated towards the simulation of the material microstructure, flow patterns and the thermal profiles involved with the friction stir welding process. The environmentally friendly characteristics of the process − viz. the absence of consumable electrodes, toxic welding fumes or harmful radiation − combined with the high quality of the welds makes this technology all the more attractive. Recently, investigations have been taken up to study the application of the FSW technology for welding ferrous materials as well. This paper presents an outline of the friction stir welding process, its current and possible future applications, as well as the recent developments in the process technology. Some experimental and modelling results for aluminium welding are also presented.

Keywords: Friction Stir Welding, Aluminium Alloys.

INTRODUCTION

Friction Stir Welding (FSW) is a relatively new welding technique invented by The Welding Institute (TWI) at Cambridge, U.K., in late 1991 and subsequently patented by them. The process involves a non-consumable rotating third body (a cylindrical tool) being plunged into the weld metal and traversed through the direction of the weld. The resulting frictional heat as well as the heat of deformation produced by the passage of the tool through the material plasticizes the materials and coalesces them to forge a continuous solid-state joint. The temperature never crosses the melting point of the materials, indeed it remains within 80% of the melting point [McClure et al, 1998]. The process may be compared with an in-situ extrusion process.

Friction stir welding was originally developed for welding aluminium and aluminium alloys. However, it is being investigated for welding of other materials as well, including ferrous and non-ferrous metals and thermoplastics. In fact, preliminary welds have been successfully made in mild steel, copper and its alloys, lead, titanium and its alloys, magnesium alloy, magnesium to aluminium, Zinc, metal matrix composites (MMCs) based on aluminium, other aluminium alloys of the 1000 (commercially pure), 3000 (Al-Mn) and 4000 (Al-Si) series, and plastics [TWI Website]. The process can be applied to produce either butt or lap joint as well as T-joint in a wide range of thickness of materials.

PROCESS DESCRIPTION

Friction stir welding has a greater resemblance to extrusion processes than to traditional fusion welding techniques. It is different from friction welding in that the rubbing action is provided by a rotating cylindrical tool that is plunged into the joint to be made and traversed along the length of the joint. Figures 1a & 1b show the schematic representation of the FSW process in butt and overlap configurations. The basic steps of the welding process are as follows:

1. the two pieces to be welded are butted (or lapped) together and are clamped to a backing plate on a suitable machine tool
2. A rotating pin tool with a broader circular shoulder is plunged into the workpieces until

the shoulder is in compressive contact with the top surface(s) of the weldpiece(s).

3. Once sufficient heat is generated, the pin tool is traversed the length of the interface forming a joint along its path.

All in all, the FSW process is analogous to a solid-phase keyhole welding technique, since a hole is generated to accommodate the pin and is subsequently filled during the welding process. However, thin sheets can be welded with a tool that has no pin and only the shoulder to cause the frictional heating. The pin is usually threaded such that it has an unscrewing motion as it rotates, but threadless pins have also been used especially for thin sheets without significant effect on the temperature field or the material microstructure.

Spindle rotation, travel rates and geometric stability being the only requirements for a machine to be suitable for the FSW process, most FSW is done on modified milling machines. However, highly sophisticated machines equipped with sensors and controllers for force and displacement controls as well as for force and torque measurements are also being manufactured. One such machine manufactured by MTS has replaced the original milling machine that was modified for FSW purposes at the University of South Carolina.

The relative motion between the shoulder of the tool and the workpiece as well as the plastic deformation of the material in the stir zone contributes to the frictional heating required to soften the material; however the relative contribution of the two sources has not yet been determined.

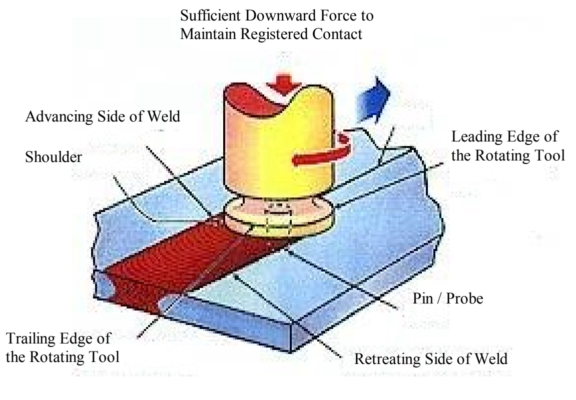

Fig.1a FSW Process in a Butt-weld Configuration (Adapted from TWI website)

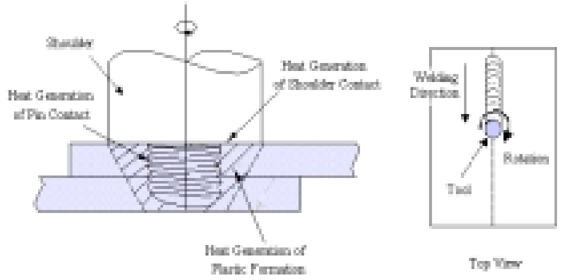

Fig.1b Schematic Representation of the Overlap FSW Process

Advantages

Most of the advantages of FSW vis-à-vis conventional fusion welding processes are primarily attributable to the fact that no melting of the material is involved:

- Because FSW is a solid-state process, the weldments are free from defects related to solidification that are common in most fusion welding process
- Absence of consumables, fumes, spatter and porosity
- Minimal residual stress and distortion of the base metal is achieved
- Welds can be made in a single pass with no specialized joint preparation
- Excellent mechanical properties as proven by fatigue, tensile and bend tests

Shortcomings

- High force requirements
- Workpieces must be rigidly clamped to backing plates
- Presence of keyhole at the end of each weld
- Welding speeds are moderately slower than those of some fusion welding processes (up to 750mm/min for welding 5mm thick 6000 series aluminium alloy on commercially available machines) [TWI Website]

WELD CHARACTERISTICS

The microstructure resulting from FSW can be categorized into the following zones: *(1)* the *weld nugget* (or the stir zone) experiencing severe plastic deformation and the highest amount of heating, *(2)* the themomechanically affected zone (TMAZ) or heat and deformation affected zone (HDAZ) which is deformed by being entrained along with the actual weld metal and also experiences some microstructural changes associated with the frictional heating [Rhodes et al, 1997, & Flores et al, 1998], *(3)* the heat affected zone (HAZ), and *(4)* the unaffected parent metal. The weld nugget is characterized by a very fine, recrystallized grain structure that is a common feature of all friction stir welds [Rhodes et al, 1997].

Unlike fusion welds, the weld nugget microstructure and the associated mechanical properties in a friction stir weld are not symmetric about the weld line. However, surface temperature fields resulting from FSW have been experimentally found to be nearly symmetric while the material flow is markedly non-symmetric. Also the mechanical properties are found to be superior to most other fusion welding techniques especially for metals that are difficult to weld [TWI Website].

CURRENT AND FUTURE APPLICATIONS

Although much of the early works on friction stir welding was done at the facilities of its patent holder TWI, research and development efforts on this technology is now being carried out all over the world. The most significant contributors to the research investments are the aerospace industry and the light-weight ship-building industry [Gould et al, 1997]. Their interest in the technology stems from the fact that most of the high strength aluminium alloys used in the aerospace industry are difficult to join using conventional fusion welding techniques while the ship-building industry can take advantage of the low distortion propensity of the FSW [Gould et al, 1997]. Automobile industry is also getting interested in the technology because of the inherent process robustness and improved mechanical properties of the FSW. However, much of the research in this field until recently has been proprietary in nature undertaken by industry labs and aimed at specific applications of interest to the organizations themselves.

A list of applications of the FSW process in different industrial sectors can be found at the TWI website. Enough literature is also available on specific use and suitability of FSW for different specific purposes.

PROCESS MODELLING

Although there has been a lot of experimental investigations into the friction stir welding ever since its invention, efforts in numerical modelling to simulate the welding process are more recent. As a result, not much modelling results are currently available in literature. However, this situation is likely to change in the near future because of the enormous interest in the process model of FSW at different academic and research organizations.

The modelling efforts have so far been 3 fold – solid mechanics based microstructure modelling, fluid dynamics based material flow modelling and thermal modelling. While the need for a unified approach towards all these models is universally acknowledged, little success has been achieved towards this goal because of the extreme difficulty in modelling the FSW process in a coupled and realistic 3-D formulation. In this paper, we will introduce the preliminary work on thermal modelling of the FSW process which may very well aid in evaluating the material microstructure in the weld nugget and the thermo-mechanically affected zones of the weld by way of predicting the time-temperature history and the thermal profile during the welding process.

Thermal Modelling

The heat generation in the friction stir welding is assumed to be a combination of two different mechanisms: (1) the friction at the tool and workpiece interfaces, and (2) the plastic deformation of the weld metal in the vicinity of the pin. However, no successful effort has been made to model the heat generation due to plastic deformation, which is rather taken as a certain percentage of the frictional heating in most papers [Colegrove et al, 2000, & Russel et al, 1999].

Some of the earliest efforts on thermal modelling of friction stir welding used the Rosenthal equation for a uniformly moving point heat source to describe the heat input [Russell et al, 1998, Gould & Feng, 1998, and McClure et al, 1998]. Chao and Qi (1998) used a finite element based model of the heat generation in which all the heat was assumed to be generated at the interface between the tool shoulder and the workpiece and the rate of heat input was assumed to vary along the radius. This approach has been followed in most other friction-based models with some additions and modifications. In this current paper, two different modelling approaches are presented — a friction-based model for a lap joint as well as a newer input torque based model for a butt joint FSW process.

Friction-based Model: In the first case, a friction-based finite element model was used to simulate the thermal profile and temperature history encountered during the overlap welding of 5454-O Aluminium alloy. The governing equation for the unsteady heat flow can be expressed as:

$$\frac{\partial(\rho c T)}{\partial t} + \nabla \cdot \left(\rho c \vec{V} T\right) = \nabla \cdot \left(k \nabla T\right) + q \qquad (1)$$

where T is temperature, c is specific heat, ρ is density, t time, $\vec{V}$ is the simulation velocity of material flow, k is thermal conductivity, and q is the moving heat generation per unit volume.

The finite element model of the unsteady heat generation at the shoulder is related to the radial distance r and the tool shoulder dimensions as follows:

$$q_{shoulder} = \frac{2 \cdot \mu \cdot F \cdot N \cdot r}{r_{shoulder}^2 - r_{pin}^2} \qquad (2)$$

where μ is the effective friction coefficient, N the spindle rotation speed of tool (in rps), F the downward force of the process assumed to be applied at the shoulder interface, $r_{shoulder}$ is the radius of the shoulder, r_{pin} is the radius of the pin, and r the distance to moving centre of the shoulder. In the current model, the heat generation at the pin interfaces is taken to be 3% of that generated at the shoulder interface.

The boundary condition used at the vertical surfaces as well as the top and bottom surface of the weld plate may be expressed as:

$$-k\frac{\partial T}{\partial n} = h(T - T_\infty) \qquad (3)$$

where n represents the x/y/z coordinates as necessary, h is the convective heat transfer coefficient and T's are temperatures. The conduction heat loss through the bottom surface to the backing plate is simplified with a large convective heat transfer coefficient.

In case of overlap welding, one encounters a thermal contact resistance at the faying surface of the sheets. A heat transfer coefficient was introduced for approximating the heat transfer rate at the faying surface by Xu et al (1999a & 1999b) and Khan et al (2000). They proposed a relationship for heat transfer coefficient, HTC , with contact pressure:

$$HTC = HTC_0 \cdot p \qquad (4)$$

where HTC_0 is defined as the basic heat transfer coefficient (4.0e6 W/m2.K, for this paper) and p the dimensionless pressure distribution at faying surface by mechanical model [Xu et al(1999a & 1999b) and Khan et al (2000)].

Input Torque Based Model: In this case, the heat input was correlated to the torque data measured during actual FSW of Al 6061-T651 and then it was attributed to the three surfaces of the tool making contact with the workpiece on the basis of the areas of contact. These interfaces are the shoulder-workpiece interface, vertical pin surface to workpiece interface and the pin bottom to workpiece interface. The underlying concepts behind these adjustments are as follows:

Torque, $$\mathrm{T} = \int_{r_i}^{r_o} (\tau r)(2\pi r)dr \qquad (5)$$

where τ is assumed to be a constant shear stress that is calculated from the torsional stress equation $\tau = \frac{\mathrm{T}r}{J}$.

The finite element heat flux can be related to the radial position r as:

$$q(r) = \omega\tau r = 2\pi\tau N r \qquad (6)$$

where N is the rotational speed in RPS.

The governing equation and the boundary conditions used for this case are similar to those used for the friction-based model.

Both the models were implemented on a commercially available finite element analysis code – ABAQUS version 5.8-1.

EXPERIMENTAL SET-UP

Both the experiments on overlap joint and butt joint were carried out on a FSW machine manufactured by MTS and equipped with sensors and controllers for achieving vertical force and/or displacement control and measurement of the vertical and horizontal forces as well as torques exerted by the rotating tool. The arrangement of the thermocouples for temperature measurement is discussed below.

Overlap Joint

Gage-36 K-type thermocouples were glued to the top surface of the top sheet (at 4 locations), the bottom surface of the bottom sheet (at 7 locations) and the top surface of the bottom sheet (taken as the middle or faying surface) at 6 different locations. On each surface, thermocouples were placed at different distances from the weld centreline; however they were made to correspond to the same location from the weld centre for each surface layer.

Butt Joint

25 gage-36 K-type thermocouples were embedded into different locations and depths in 3 layers on the trailing side weld-plate. The weld-pieces were 0.32 inch thick, 4 inch wide and 2 ft long and the thermocouples were placed in 3 layers within a plate – 0.08 inch from top and bottom surfaces and the mid-plane of the plate. The positioning of the thermocouples was dictated by experimental data on material flow from previous experiments performed at the USC.

RESULTS AND DISCUSSION

Friction Based Model – Overlap Joint

Fig.2a through Fig.2e compare experimental data and the simulation results. It can be seen that the temperature distribution at different layers – viz. top surface of top sheet, middle surface and the bottom surface of the bottom sheet – show comparable trends for both experimental and modelled data although the experimental temperature profile is flatter than the simulation results. This is caused by a rapid decrease in contact pressure and consequently the thermal contact conductivity with distance from the tool shoulder. The experiment yielded a maximum temperature of about 520°C while the simulation yielded a maximum temperature of about 492°C. However, it can be seen that farther from the weld centreline, the measured temperatures demonstrate a wider difference between different layers while the simulation results show temperature curves pretty closely spaced (Fig.2d & Fig.2e). This narrow temperature difference in the simulated results essentially depicts the 2-D idealization of the heat flow associated with very thin sheets whereas the wider spread for experimental results is possibly caused by the gap created between sheets as well as between the sheet and the backing plate by the thermocouples glued to the sheet surfaces.

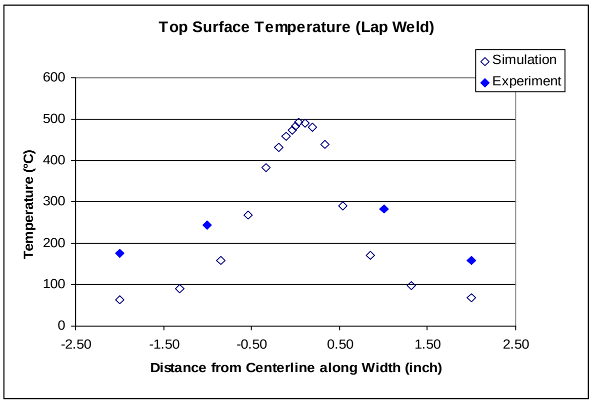

Fig. 2a Temperature Profile for Top Surface

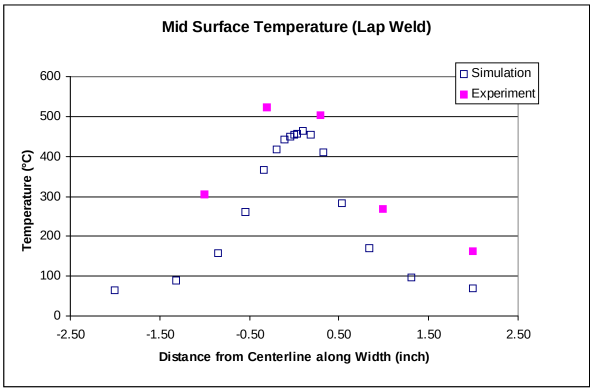

Fig. 2b Temperature Profile for Mid Surface

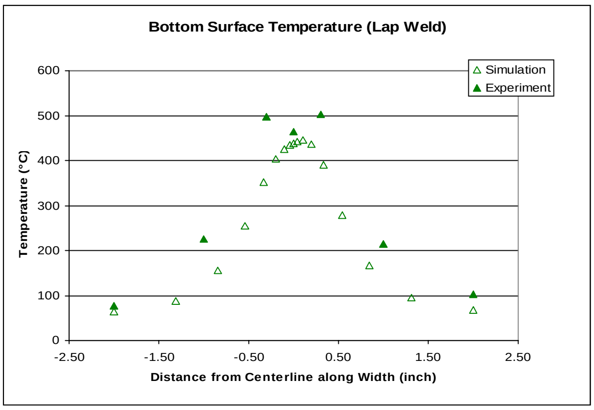

Fig. 2c Temperature Profile for Bottom Surface

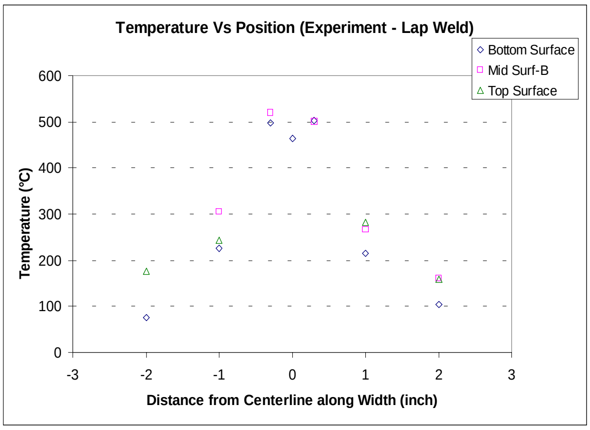

Fig. 2d Experimental Temperature Profile

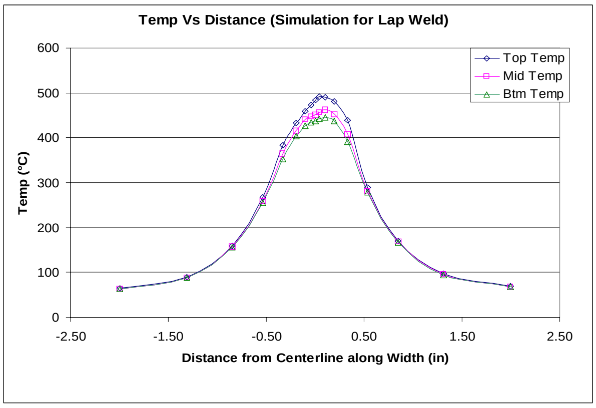

Fig.2e Simulated Temperature Profile

Input Torque Based Model – Butt Joint

Fig.3a and Fig.3b show the experimental and simulated temperature histories respectively. The maximum temperatures obtained in the simulation are somewhat lower than the experimental results. This probably calls for the incorporation of the heat generation by plastic deformation of the material in the heat model.

Fig. 4a and Fig. 4b show the spatial temperature distribution for the experiment. A somewhat unexpected trend is seen here in that the top layer temperature falls below the temperatures of the other layers a certain distance from the weld-centerline both for the maximum temperature plot (Fig.4a) and for the specific time instant plot (Fig4b). The trend is not supported by the simulation results where the top layer always has a higher temperature profile than the middle or bottom layers (Fig.5). In the experimental set-up, the bottom-layer thermocouples were located closest to the starting point of the weld while the top layer thermocouples were located the farthest. The time-temperature data was then shifted using the rate of linear travel of the tool and consequently the heat source. This fact combined with the rather unexpected temperature profile for the top layer probably implies that the speed at which heat diffusion takes place could be significantly different from the speed of the tool traverse and therefore calls for some more experimentation with the positioning of the thermocouples.

Apart from the apparent discrepancy in the top layer curve, the trends of the spatial temperature profiles from the experiment and the simulation are reasonably similar-looking. About 40mm away from the weld centreline, all the temperatures fall below 150°C and the curves become densely packed. However, in the simulation, the temperature profiles come close to each other much more rapidly than in the experiment. Also in the simulation, the curves almost overlap each other beyond 20 mm from the weld centreline. This is perhaps caused by the simplifying assumption of a high constant convective coefficient at the bottom surface of the weld-plate to represent the heat loss to the backing plate. In reality, this may be varying with the varying degree of force and moving heat input caused by the moving tool.

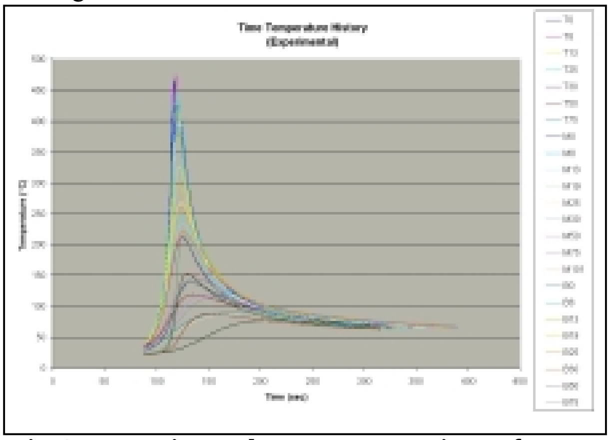

Fig. 3a Experimental Temperature History for Butt Weld of Al 6061

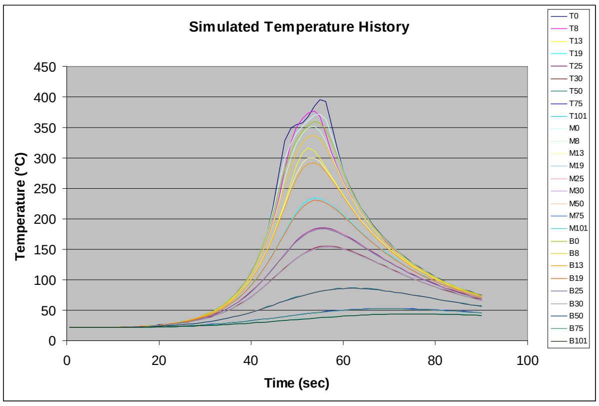

Fig. 3.b Simulated Temperature History for Butt Weld of Al 6061

CONCLUSION

Finite element models of the friction stir welding based on frictional heating and input torque were developed for lap joint and butt joint configurations respectively. The models were implemented on ABAQUS. The simulated outputs are compared against experimental results. Encouraging match was demonstrated between simulation and experimental data. However, the friction based model has the inherent shortcoming of having to play with the unknown friction factor whereas the input-torque based model provides a good result without any such manipulations. Inclusion of heat generation from plastic deformation of the material in the weld nugget may improve the results farther and should be investigated.

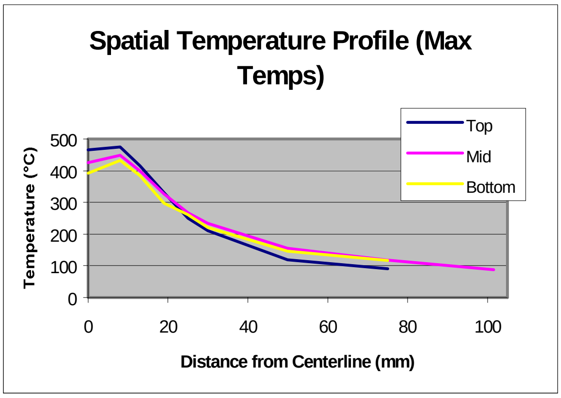

Fig. 4a Experimental Thermal Profile

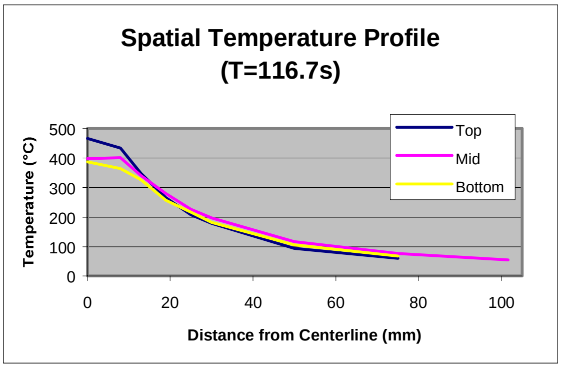

Fig. 4a Experimental Thermal Profile at an Instant

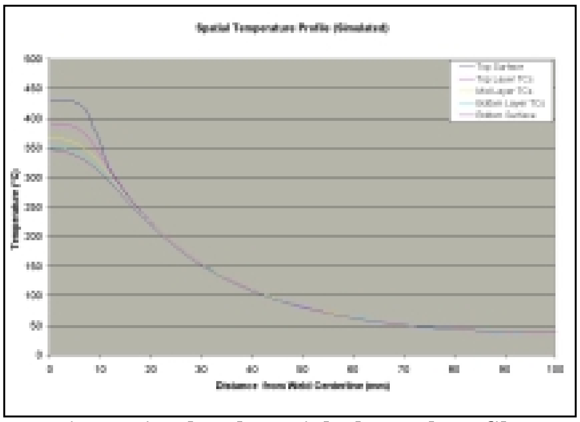

Fig. 5 Simulated Spatial Thermal Profile

REFERENCES

Chao, Y.J., & X. Qi (1998), Thermal and Thermo-Mechanical Modeling of Friction Stir Welding of Aluminum Alloy 6061-T6, *J. Materials Processing & Manufacturing Science,* 7(2), pp.215-233, Technomic Publ Co, PA, USA, Oct 1998

Colegrove, P., M. Painter, D. Graham, & T. Miller (2000), 3 Dimensional Flow and Thermal Modelling of the Friction Stir Welding Process, 2nd International Symposium on Friction Stir Welding, Gothenburg, Sweden, 26-28 June 2000

Flores, O.V., C. Kennedy, L.E. Murr, D. Brown, S. Pappu, B.M. Nowak, & J.C. McClure (1998), Microstructural Issues in a Friction-Stir-Welded Aluminum Alloy, *Scripta Materiala*, 38(5), pp.703-708, Elsevier Science Ltd, 1998

Gould, J.E., & Z. Feng (1998), Heat Flow Model for Friction Stir Welding of Aluminum Alloys, *J. Materials Processing & Manufacturing Science,* 7(2), pp. 185-194, Technomic Publ Co, PA, USA, Oct 1998

Gould, J.E., T.J. Lienert, & Z. Feng (1997), Recent Developments in Friction Stir Welding, Paper No. 98AMTC-66, Society of Automotive Engineers, Inc, 1997

Khan, J.A., Xu, L., Chao, Y., and Broach, K., 2000, Numerical Simulation of Resistance Spot Welding Process, *J. of Numerical Heat Transfer*, Part A., Vol. 37, No. 5, pp. 425-446

Liu, G., L.E. Murr, C-S. Niou, J.C. McClure, & F.R. Vega (1997), Microstructural Aspects of the Friction-Stir Welding of 6061-T6 Aluminum, *Scripta* Materiala, 37(3), pp. 355-361, Elsevier Science Ltd, 1997

McClure, J.C., W. Tang, L.E. Murr, X. Guo, Z. Feng, & J.E. Gould (1998), A Thermal Model of Friction Stir Welding, 5th International Conference on Trends in Welding Research, Pine Mountain, Georgia, 1-5 June, 1998, pp.590-596

Rhodes, C.G., M.W. Mahoney, W.H. Bingel, R.A. Spurling, & C.C. Bampton (1997), Effects of Friction Stir Welding on Microstructure of 7075 Aluminum, *Scripta Materiala, V.36, No. 1, pp. 69-75*, Peragmon Press, 1997

Russell, M.J., & Shercliff, H.R. (1998), Analytical Modelling of Friction Stir Welding, INALCO '98: 7th International Conference: Joints in Aluminum, Vol.2, pp. 185-217, Cambridge, UK, 16 April, 1998

Russell, M.J., & Shercliff, H.R. (1999), Analytic Modeling of Microstructure Development in Friction Stir Welding, 1st International Symposium on Friction Stir Welding, Thousand Oaks, Cal, June 1999

TWI Website, http://www.twi.co.uk/j32k/unprotected/band_1/fswintro.html

Xu, L., and Khan, J.A. (1999a), Nugget Growth Model for Aluminum Alloys during Resistance Spot Welding, *Welding Journal*, 78(11), 367-s to 372-s

Xu, L., Khan, J.A., Chao, Y.J., and Broach K. (1999b), Numerical Study of Thermal Modeling of Resistance Spot Welding Utilizing Coupled Thermal-Electrical-Mechanical Analysis, *ASME HTD-Vol. 364-3, Volume 3,* pp 395-402