RESEARCH OF TEMPERATURE DISTRIBUTION DURING FRICTION STIR WELDING OF 2 MM AW 6082 SHEETS

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Abstract

The purpose of this article is to research temperature field during friction stir welding (FSW). Experimental FSW of 2 mm sheets was provided for temperature determination. Aluminium alloy AW 6082 was chosen as a material for workpieces. Temperature was measured by thermocouples. Influence of the tool rotation speed on temperature distribution was estimated using experimental results. An analytical heat source model developed before was improved; capability of the model in comparison with experiment was proved. The temperature distribution was calculated by means of numerical simulation. The simulation model was compared with experimental result. The results of numerical simulation are in good agreement with experimental results. Maximum temperature distribution along and across the weld centreline was estimated using developed FE-model.

Keywords: Friction Stir Welding, FSW, Simulation, Temperature Distribution, Aluminium Alloys

1. INTRODUCTION

Lightweight materials usage has a lot of potentials for aviation, automobile industry and mechanical engineering in order to reduce fuel consumption. Application of new welding methods is necessary to meet strength and reliability requirements for structures which are made of lightweight materials. FSW is a new method for such materials joints producing.

The most important problem during FSW process is the non-uniform distribution of the properties in the weld area. The temperature is the most significant factor which influences the properties of the produced joint. Information about temperature distribution is necessary to predict the joints microstructure, mechanical properties of joints and whole structures.

The aim of this study is to research temperature distribution in FSW joints. The temperature determination is possible by using thermocouples but it is difficult to measure temperature in the zone of plastic deformation, in particular under the tool shoulder and along the weld centreline. Influence of the rotation speed is estimated using experimental results. Numerical simulation enables an additional ability of temperature determination in the weld joints including the zone under the tool shoulder and along the weld centreline.

2. ANALYTICAL HEAT SOURCE MODEL

An analytical heat source model of FSW [1] was improved by taking into account not only the friction at the contact surfaces or close to the contact surfaces under the tool shoulder and at the tool probe sides but also the influence of the plastic deformation in the weld nugget on heating of the workpieces.

Heat generation equation is as follows:

$$q_{gen} = q_1 + q_2 + q_3 + q_4 \qquad (1)$$

where q_1 is the heat generation from shoulder, W; q_2 is the heat generation from probe side, W; q_3 is the heat generation from probe tip, W; q_4 is the heat generation as a result of plastic deformation, W.

Heat generation from shoulder equation is as follows:

$$q_1 = \frac{2}{3}\pi\omega\left(R^3_{shoulder} - R^3_{probe}\right)\left(1+\tan\alpha\right)\left((1-\delta)\mu\sigma + \delta\frac{\sigma_{yield}}{\sqrt{3}}\right) \tag{2}$$

where ω is the angular velocity, rad s^{-1}; $R_{shoulder}$ is shoulder radius, m; R_{probe} is probe radius, m; μ is the friction coefficient, σ is the contact pressures, Pa; σ_{yield} is yield stress, Pa; α is shoulder cone angle and δ is the contact state variable.

Heat generation from probe side equation is as follows:

$$q_2 = 2\pi\omega R^2_{probe} H_{probe}\left((1-\delta)\mu\sigma + \delta\frac{\sigma_{yield}}{\sqrt{3}}\right) \tag{3}$$

where H_{probe} is pin length, m.

Heat generation from probe tip equation is as follows:

$$q_3 = \frac{2}{3}\pi\omega R^3_{probe}\left((1-\delta)\mu\sigma + \delta\frac{\sigma_{yield}}{\sqrt{3}}\right) \tag{4}$$

Heat generation due to plastic deformation ranges from 2 to 20 % [2, 3, 4] and is as follows:

$$q_4 = k\left(q_1 + q_2 + q_3\right) \tag{5}$$

where k is the plastic deformation calibration coefficient ranges from 0.02 to 0.2.

3. EXPERIMENTAL PROCEDURE

FSW experiment was performed in Brandenburg University of Technology. Plates made of EN AW 6082 T6 aluminum alloy with the dimensions 2x400x125 mm were welded with different rotation speed of tool. The tool was made of a tool steel, diameter of the shoulder is 12.5 mm and cone angle of shoulder is 3 degrees. The probe length is 1.8 mm, diameter of the probe is 4 mm. Plates were placed on backing plate and fixed using clamps. The FSW parameters used during experiments are listed in Table 1.

Table 1. FSW conditions

Rotation speed, rpm	Welding speed, mm/min	Axial force, kN	Depth of plunge, mm	Tilt angle, degree
710; 1120	400	5	0.1	2

The temperature was measured by Type K thermocouples placed on both the advancing (AS) and the retreating sides (RS) symmetrically relative to the weld centerline. The scheme of the thermocouples positions is shown in Fig. 1.

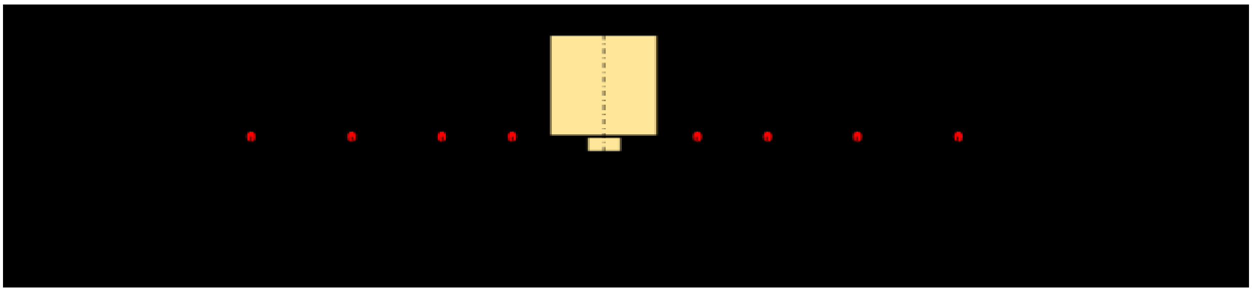

Fig. 1. Thermocouples position

Temperature cycles during FSW process with 710 rpm and 1120 rpm are shown in Fig. 2 and Fig. 3 respectively.

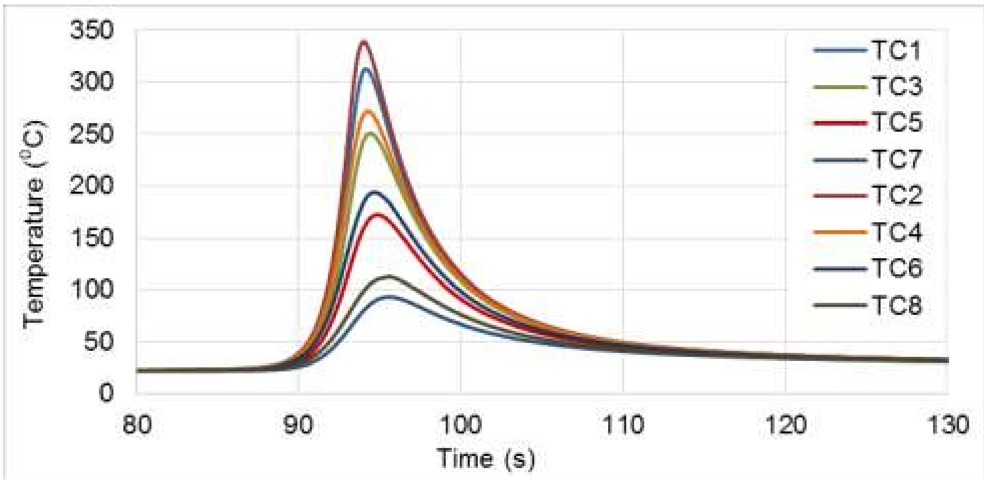

Fig. 2. Temperature cycles during FSW at 710 rpm

It was noticed that the temperature on the AS and the RS during FSW at 710 rpm was different. The maximum temperature of 339 °C was measured on the AS at a distance of 8 mm from the weld centerline and the maximum temperature of 313 °C was measured on the RS.

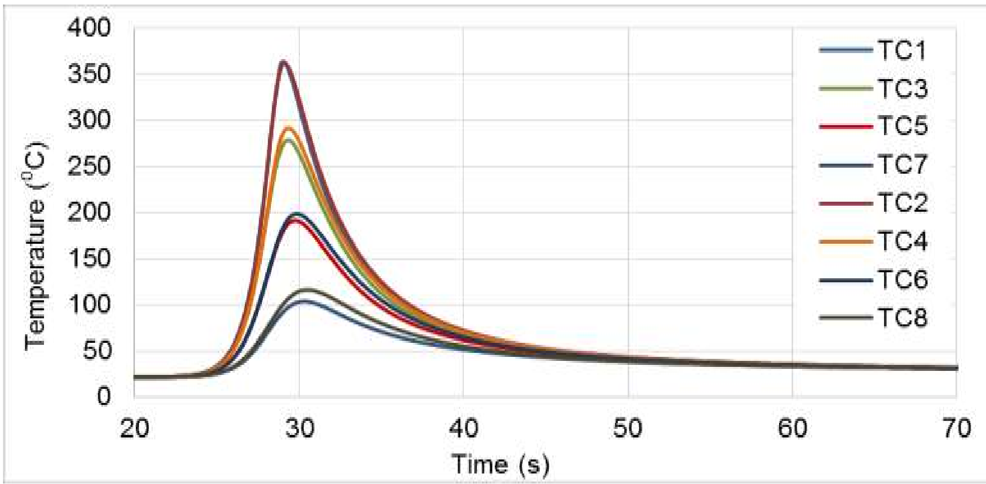

Fig. 3. Temperature cycles during FSW at 1120 rpm

The maximum temperature of 363 °C was measured on the both the AS and the RS during FSW at 1120 rpm. The maximum temperature growth was about 10% when increasing of the rotation speed was more than 50% (from 710 to 1120 rpm). According to Eq. 1 heat generation and temperature should increase in proportion to the rotation speed, but it did not occur. The reason for such a small temperature growth is the changing of contact state variable δ and yield stress σ_{yield}. It was noticed that the temperature difference between the AS and the RS decreased with increasing rotation speed.

4. FINITE ELEMENT SIMULATION OF THERMAL PROCESS

4.1. FE – simulation

Simulation was performed using Ansys Version 14 software. The geometric plate model with the dimensions of 2x237.6x118.8 mm was built. In the present thermal analysis, the workpiece was meshed using a simplex element called SOLID70. A FE-model consisted of 116490 elements and 142188 nodes was generated. Heat source model for simulation is symmetric therefore it is enough to build it only for one sheet. Influence of the second sheet was compensated with adiabatic boundary conditions. The geometry of backing plate and clamps were not built. Influence of backing plate on the temperature distribution was compensated by means of the Newton's boundary conditions with convection coefficient value of $9{\cdot}10^{-4}$ W/(m$^2{\cdot}$K). This boundary conditions were applied to surface of the sheet to compensate the backing plate contact. Also Newton's boundary conditions with convection coefficient which is shown in Fig. 4 were applied to other sheet surfaces.

The thermophysical properties of workpiece material used in simulation (thermal conductivity λ, specific enthalpy H, convection coefficient h_f) are presented in Fig. 4.

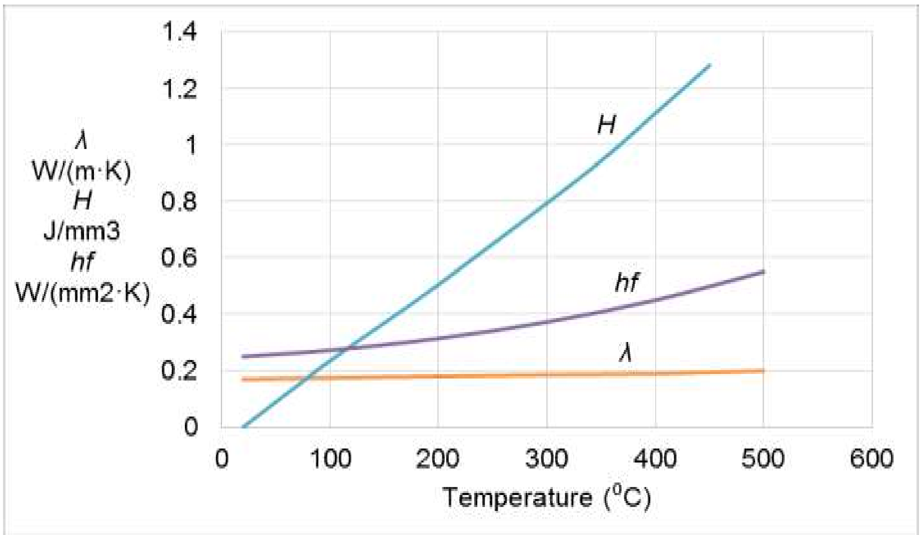

Fig. 4. The thermophisical properties of workpieces material

Heat generation value used in finite element simulation was calculated using Eq. 1. The contact state variable of 0.5 and the plastic deformation coefficient of 0.1 were chosen for the calculations. Simulation was performed for rotation speed of 710 rpm.

4.2. Simulation results

The maximum temperature distribution at the plate surface along the weld centreline during FSW process is presented in Fig. 5.

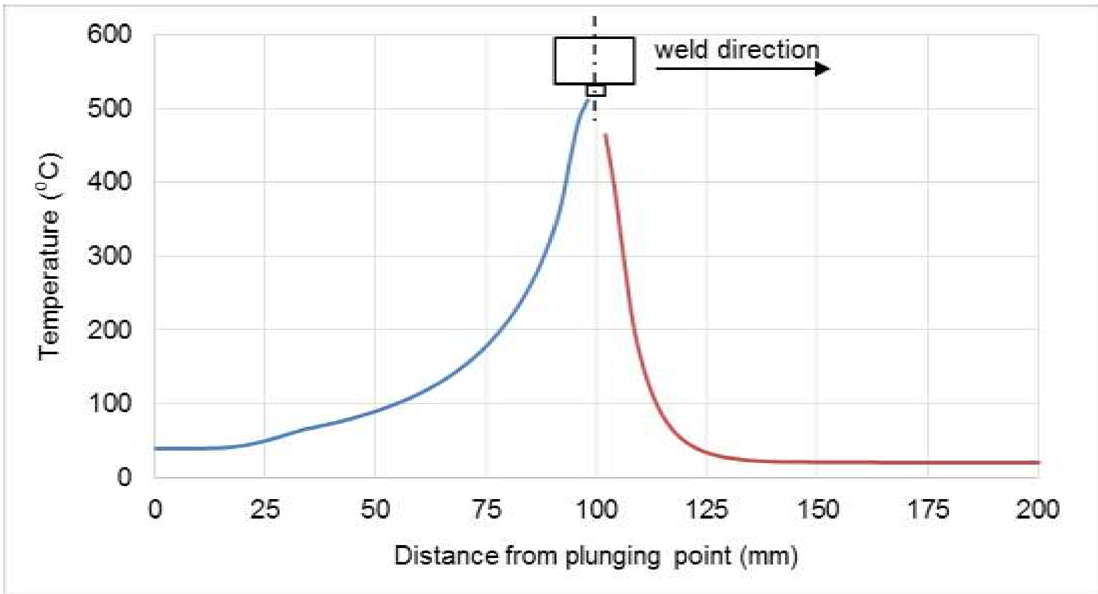

Fig. 5. Maximum temperature distribution along the weld centreline

The maximum temperature distribution in front of tool is marked with red line and the maximum temperature distribution behind of the tool is marked with blue line. The calculated maximum temperature during FSW process of 511 ^{0}C presented in Fig. 5 is reached under the tool shoulder just behind the probe. The calculated minimum temperature of 304 ^{0}C shown in Fig.5 is reached under the tool shoulder just behind the shoulder.

The comparison of numerical maximum temperature distribution and measured value at the surface of the welded plates across the weld centreline is shown in Fig. 6.

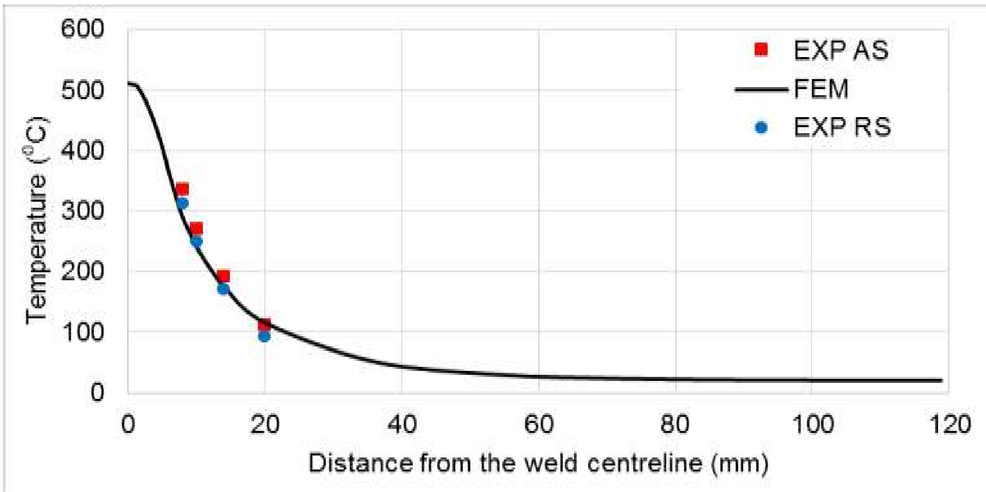

Fig. 6. Comparison of numerical maximum temperature distribution and measured value

The mean deviation at a distance of 8 mm from the weld centerline is 6.2 %. The mean deviation at a distance of 10 mm from the weld centerline is 7.8 %. The mean deviation at a distance of 14 mm from the weld centerline is 7.3 %. The mean deviation at a distance of 20 mm from the weld centerline is 9.3 %.

The comparison of calculated and measured temperature cycles at the surface of the welded plates across the weld centreline is shown in Fig. 7.

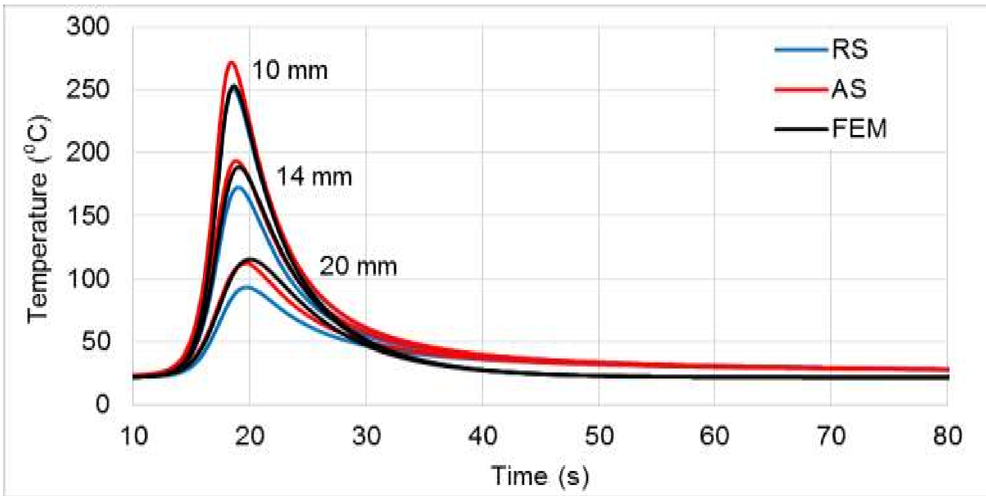

Fig. 7. Comparison of calculated and measured temperature cycles

The simulation results are in good agreement with experimental results. There is visible deviation in the range below 100 ^{0}C. The absolute deviation in this area is about 20 ^{0}C therefore this deviation is negligible.

CONCLUSIONS

The temperature on the AS and the RS during FSW is different. This temperature difference between the AS and the RS decreases with the increasing of the rotation speed. The maximum temperature growth is about 10 % when increasing of the rotation speed is more than 50 % (from 710 to 1120 rpm). The reason for such a small temperature growth is the changing of contact state variable δ and yield stress σ_{yield}. The maximum temperature of 511 ^{0}C is reached under the tool shoulder just behind the probe during FSW process with the rotation speed of 710 rpm. The minimum temperature of 304 ^{0}C is reached under the tool shoulder just behind the shoulder during FSW process with the same rotation speed.

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