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Sürtünme Karıştırma Kaynağı Yapılmış Alüminyum Alaşımlarının Isı Akışının Modellemesi ve Pratik Doğrulaması

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Anahtar Kelimeler
Sürtünme Karıştırma Kaynağı,
Modelleme,
Alüminyum Alaşımı

Özet: Bu makalede AA 6061-T6 alüminyum alaşımının sürtünme karıştırma kaynağının Comsol Multiphysics 3.5a ile yapılan üç boyutlu modellemesi anlatılmıştır. Simülasyon kaynak edilecek iki alüminyum levhasını, kaynak takımını ve kaynak takımının omuz kısmını içermektedir. Isı transferi ve Newtonyen olmayan akış denklemleri aynı anda çözülmüştür. Kaynak edilen plakaların altındaki taşınım ısı transfer katsayısı ve kaynak takımının omuz kısmı tarafından sisteme verilen ısı miktarı basit ve pratik bir ısıl doğrulama yöntemiyle belirlenmiştir. Kaynak edilen plakalar boyunca oluşan ısı akışı değişik kaynak koşulları için gösterilmiştir. Kaynak takımı omzu ve ucu etrafında oluşan metal akışı değişik takım dönme hızları için gösterilmiştir. Bu çeşit bir pratik doğrulama yöntemi kaynak mühendisine neredeyse mümkün olabilecek bütün kaynak koşullarını simüle edebilecek imkanı pahalı deneyler yapmadan sağlayabilmektedir. Sunumu yapılan doğrulama ve model sayesinde mühendislik zamanından tasarruf yapılabilecektir.

Practical Validation and Heat Flow Modeling of FSW'ed Aluminum Alloys

Keywords
FSW,
Modeling,
Aluminum Alloy

Abstract: This paper describes the application of the CFD code, Comsol Multiphysics 3.5a, to modeling the three-dimensional heat and metal flow in friction stir welding (FSW) of AA6061-T6 aluminum alloy. The simulation consists of two aluminum plates to be welded, tool and its shoulder. Heat transfer and non-newtonian flow equations were solved simultaneously. The convective heat transfer coefficients underneath the welded plates and the heat given to the system by the tool shoulder were determined by the help of a simple and practical thermal validation. The heat flow along the plates is depicted with changing welding conditions. The flow around the tool pin and shoulder was shown for several different tool rotation rates. This kind of practical validation method helps the welding engineer to simulate nearly all the possible welding conditions without performing expensive experiments. Information obtained from the presented validation and the model can save a lot of engineering hours.

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1. Introduction
FSW process was developed and patented by The Welding Institute in 1991 [1]. 'A rotating pin, attached to a shoulder piece, is translated along the joint line, causing localized plastic deformation, whilst frictional heating occurs due to contact between the tool and the material. In this process, welding zone is completely isolated from atmosphere which minimizes the formation of voids and large distortion in the weld zone. This new welding technique is extensively applied to aerospace, automobile and shipbuilding industries [2]'.

Some authors constructed pure thermal models [3-8]. CFD (Computational Fluid Dynamics) models were also studied [2,9-19] In the CFD models, mostly the Eulerian approach was utilized.

There are some FSW experiments found in the literature as well [4-6,16,20,21]. These experiments were used either for validation purposes or for improving the numerical analysis. For FSW process some authors performed their own experiments [4-7,20] and some used the experiments from the literature [2,22]. This kind of validation is used in most of the numerical applications for the solutions to have a realistic meaning. In other welding methods, also validation has been used. One can find numerical solutions of the weld pool [23-25] of Gas Tungsten Arc Welding (GTAW) and Gas Metal Arc Welding (GMAW) in the literature.

Roy et al. solved CFD equations by way of carreau viscosity model [2]. Several authors utilized inverse hyperbolic sine law in their CFD models [9,11-13,18,26,27]. Schmidt and Hattel utilized power law method in their work [16]. Dörfler proposed a completely different method to solve CFD equations [19].

There are authors who wrote their own code for solving the metal flow problem in FSW process [17,18]. The aim of this present study is to show the applicability of Comsol© Software by means of the power law viscosity model. The only previous work using the power law viscosity model is the one Schmidt and Hattel proposed [16]. In their model, they solved the FSW process for AA7075-T6 aluminum alloy.

In this present study Comsol© 3.5a has been utilized for solving the metal flow problem occurring in FSW process of AA-6061-T6 aluminum alloy via the power inverse hyperbolic sine law model.

2. Numerical modeling

The model geometry includes three-dimensional pieces in a Cartesian coordinate system; a tool and an aluminum plate (250; 150; 8 mm) The tool is comprised of a 65 mm long shoulder which is 30 mm in diameter. The attached tool pin (probe) has a diameter of 9 mm and a height of 7 mm extending down from the shoulder with a screw thread pushing the adjacent aluminum downwards. The whole model is shown in Figure 1 and the enmeshed views of the plates and the tool are given in Figure 2. The tool material is made of H-13 tool steel. AA 6061-T6 alloys are taken as the plate material.

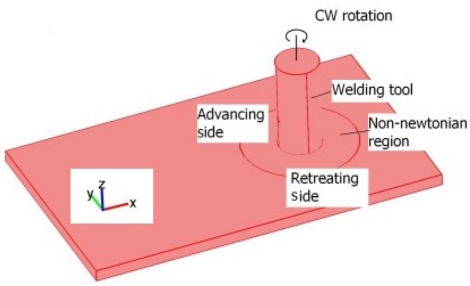

Figure 1. Computational domain, welded plates and welding tool.

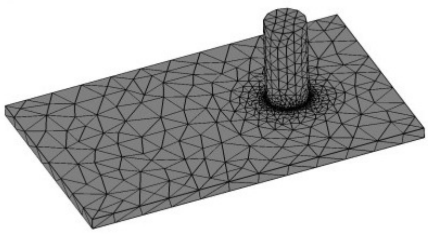

Figure 2. Enmeshed domain

A Eulerian steady-state model was constructed. In this modeling approach the welding tool was kept fixed and the plates were moved in the opposite welding direction. The energy equation in the present model was solved by Thermal Pseudo Mechanical (TPM) model approach [16]. In addition to the shoulder surface heat generation, tool pin surface heat generation was utilized.

In the present study the validation of the numerical models was performed by way a simple experiment whose temperature measurements are achieved by an infrared thermometer. The applied tool rotation rate is 800 rpm and the welding speed is 12.5 mm/min.

In the present model, due to the existence of the very low strain-rate outside of the Thermo-Mechanically Affected Zone (TMAZ) and the high strain-rate around the tool pin, the power law viscosity model was assigned to the model. The model was implemented using general Heat Transfer & Chemical Engineering (Non-Newtonian flow) modules in Comsol 3.5a [28].

The Heat Transfer and metal flow equations were fully coupled and solved simultaneously. In this present work inverse hyperbolic sine law viscosity model was chosen. The viscosity equation constants of aluminum alloy are given in reference [17].

2.1 Physical properties of aluminum alloys

Thermal conductivity (k) for steel backing plate and the tool was taken as 44.5 W/m K, specific heat (Cp) was set to 475 J/ kg K. The densities of steel and aluminum were taken as 7850 and 2700 kg/m3, respectively. The thermal conductivity and specific heat of AA6061-T6 were taken from reference [17]. which gave the most realistic thermal profile.

2.2 Key boundary conditions

2.2.1 Heat transfer:

2.2.1.1 The convective heat transfer coefficients over and underneath the welded plates

The convective heat transfer coefficient beneath the welded plates were determined by way of a simple calibration with respect to the experimental temperatures and taken as 200 W/m2 K. The upper heat transfer coefficient was taken as 6 W/m2 K.

2.2.1.2 The heat generated by the shoulder

The heat generated by the shoulder was given by the equation (1) [16]. Temperature dependent yield stresses of AA6061-T6 were taken from reference [29] and are slightly modified to give comparable temperatures with respect to the experiment.

$$q_{shoulder} = \omega r \sigma(T) / \sqrt{3} \quad (1)$$

Here, stands for the rotational speed in rad/s, r denotes the radial distance from the centre of the tool shoulder in m and (T) explains the temperature dependent yield stress of aluminum alloy in Pa.

2.2.1.3 The heat dissipated from the tool shoulder to the machine

The heat dissipation was simulated by choosing a convective heat transfer coefficient according to the reference [30]. The chosen coefficient at the upper part of the tool is 10000 W/m2 K. The other boundaries of the tool were chosen to be insulated.

2.2.1.4 The convective heat transfer coefficient from top and bottom of the plates to the air

The lower convective heat transfer coefficient was taken as 200 W/m2 K whereas the upper convective heat transfer coefficient was chosen to be 10 W/m2 K.

2.2.1.5 The room temperature

The room temperature was taken as 293 K.

2.2.2 Non-Newtonian flow

The velocity boundary conditions for the tool and the pin were applied as in the model proposed in [2].

In the present study the tool rotation was taken as a clockwise rotation. Actually the tool rotation was applied to the two semi-circles on top of the two plates which were to be welded. The pin rotation was applied to the adjacent lateral surfaces of the aluminum plates and to the aluminum surface right below the pin. The tool shoulder and pin movements were not taken into account in the Non-Newtonian flow problem.

The translational welding speed of the tool and the pin was applied to the problem domain as the inverse translational speed of the plates which was given as -u_weld (longitudinal welding speed).

$$\left[\eta = \frac{1}{\alpha \dot{\gamma} \sqrt{3}} \sin h^{-1} \left(\frac{\dot{\gamma} \exp(Q/(RT))}{\sqrt{3} A} \right)^{1/n} . \right] \quad (2)$$

The viscosity is calculated according to the inverse hyperbolic sine law (Equation 2). This equation represents how viscosity changes with temperature and motion, and is taken from Ref [18]. Here, n is the exponential coefficient which is taken as 3.55, denotes the shear rate in units of 1/s. The coefficients α and A are set to 4.5×10-8 1/Pa and 8.86×108 1/s respectively. Q is activation energy and equal to 1.45 ×105 J/mol, R is universal gas constant and equal to 8.31451 J/(mol×K). These coefficients are also taken from reference [17]. Shear thinning behavior of the plasticized aluminum is well represented by this equation.

Inside the Non-Newtonian region (See Figure 1) the viscosity is computed according to the Eq. (2). Outside this region the viscosity is set to 1x10^8 Pa s.

3. Validation

Validation of the model was performed by a simple experimental setup. Over the welded plates 35 nodes were marked with a black permanent marker in order to make the surface emissivity close to unity (Figure 3). Experimental measurement and welding are performed as shown in Figure 4.

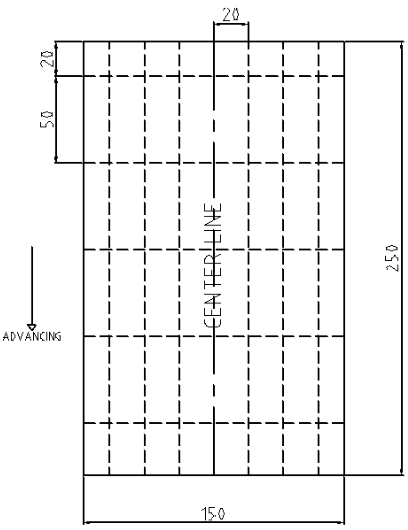

Figure 3. Experimental domain

Figure 4. Experimental temperature measurement

The comparison of the experimental and model temperatures are shown in Figure 5, 6 and 7

The temperatures along the lines 20 mm, 40 mm and 60 mm away from the centerline are compared to validate the model (Figures 5, 6 and 7). The applied tool rotation rate is 800 rpm and the welding speed is 12.5 mm/min.

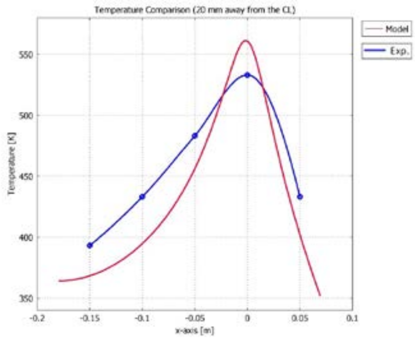

Figure 5. Temperature comparison for the line 20 mm away from the CL

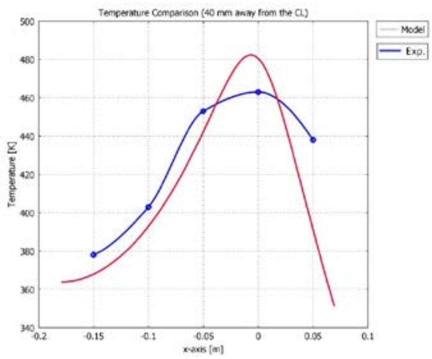

Figure 6. Temperature comparison for the line 40 mm away from the CL

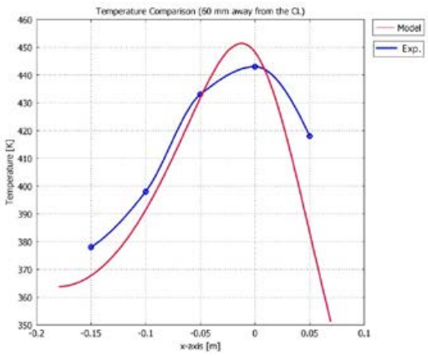

Figure 7. Temperature comparison for the line 60 mm away from the CL

Although the temperature measurements are done in 4 minutes interval (measuring points are 50 mm away from each other on the welding advancement direction.) the experimental and the model temperatures are quite close to each other. This kind of validation saves considerable time without setting up a data collection system.

4. Results and discussion

After the validation has been done and good results have been found, one can easily investigate the thermal and flow behavior of the welded plates at different welding conditions. Some of the results are presented in this section. The temperature rise with increasing tool rotation rate can be seen from the Figure 5. Every 200 rpm increase in the tool rotation rate results in a 10 degrees Kelvin rise on the line 20 mm away from the centerline.

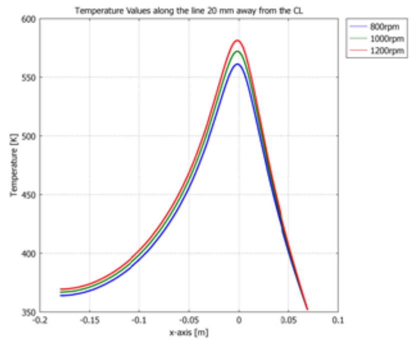

Figure 8. Temperature distribution along the line 20 mm away from the centerline

In Figures 9, 10 and 11 one can find the results of the metal flow equations. The streamlines starting from x=0.03 m, y=0.01m and z=0.0075 m are depicted for 800, 1000 and 1200 rpm tool rotation rates.

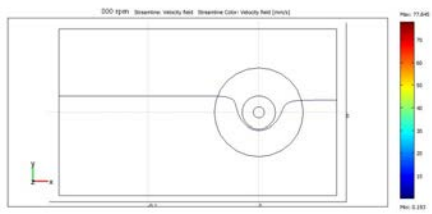

Figure 9. Metal flow streamline for 800 rpm tool rotation rate

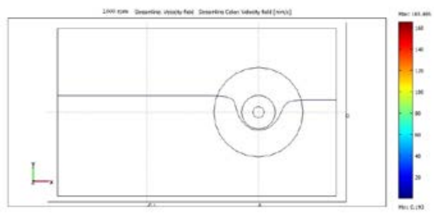

Figure 10. Metal flow streamline for 1000 rpm tool rotation rate

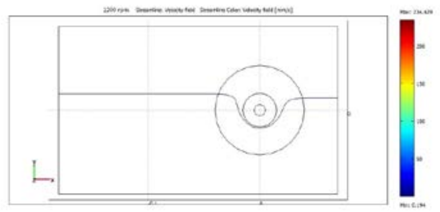

Figure 11. Metal flow streamline for 1200 rpm tool rotation rate

The influence of the rising tool rotation rate can easily be observed from the figures.
After establishing such a model by the help of a practical validation method explained in this work, the welding engineer can analyze the thermal and metal flow behavior for different welding conditions.

5. Conclusions

A Eulerian thermal and CFD model was constructed to simulate the heat flow and the aluminum flow around the tool pin and shoulder of FSW apparatus using inverse hyperbolic sine viscosity model.

The applicability of this simple validation procedure helps welding engineer to design his weldment in a practical way.

Streamlines that represent the metal flow can give the welding engineer an opportunity to predict the viscous behavior of the plasticized aluminum without making experiments.

The heat flow along the welded plates is easily and realistically simulated by using the practical validation procedure. The heat flow along the plates is depicted with changing welding conditions. The flow around the tool pin and shoulder was shown for three different tool rotation rates. This kind of practical validation method helps the welding engineer to simulate nearly all the possible welding conditions without making expensive experiments. Obtained information from the presented validation and the model can save substantial engineering hours

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