Temperature and thermal stress distribution in underwater friction stir welding of aluminium plates

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Abstract. This paper studies the effect of ambient operating conditions on temperature and thermal stresses generated in friction stir welding (FSW) of aluminium alloy plates. AA1050 plate was used with 120×60×3 mm dimensions. Both plates were joined with butt weld in air and underwater ambient conditions. Finite element analysis software COMSOL Multiphysics was used to obtain the transient temperature and thermal stresses induced inside the plates during welding under the two conditions. The effect of frictional heat generated on different parts of weld tool was determined. The results show that weld tool pin has the highest temperature in both the ambient conditions and that the thermal stress and heat affected zone was reduced in case of water.

1. Introduction

Metal joining process is a very important process in any manufacturing industry. The reliability of product depends on the mechanical properties of the joint. Joining process can be carried out either by use of fasteners or by welding. Most of the welding techniques involve local melting of base metals with little or no pressure to form the weld joint. Friction stir welding (FSW) belongs to another class of metal welding called solid-state welding wherein the base metals do not reach up to their melting. Both heat and pressure are applied in this process. This process was developed by The Welding Institute (TWI) in 1991[1] to weld materials that were difficult to weld by conventional methods. This technique was initially applied to aluminium alloys but now can be implemented over a wide range of materials [2-3].

In FSW, a rotating tool with a specially designed pin and shoulder is inserted into the border onedges of sheets or plates to be joined and subsequently traversed along the joint line. The required heat is generated by the friction between the surface of tool and workpiece which are coming in contact. FSW process parameters which affect the joint qualities are tool shape, tool travel speed, spindle rotation speed and applied force [4]. The material which gets soften due to heat, is stirred with the help of rotating pin. Due to low temperatures involved in FSW, the weld quality is superior to other processes [5]. Though heat generated is less compared to conventional process but it is enough to soften the material. This softening causes decrease in the mechanical properties by increasing the dissolution of strengthening precipitate [6-7]. To decrease this phenomenon additional cooling methods are used. By using these cooling methods, the maximum temperature is decreased, resulting in the enhanced mechanical properties. Water is a easily available fluid with high convective heat transfer coefficient which can be used as a cooling medium for friction stir welding.

Underwater friction stir welding is a variation of normal friction stir welding in which water works as an ambient medium. Tokisue et al. [8] were first to use water in a friction joining technique. In their research, they joined Al-6061 in rotary friction weld in underwater condition and showed that enough
heat could be generated even in underwater conditions. They further showed that underwater weld strength could reach up to 86% of base metals while in case of air they were able to get only 82%. Zhang et al. [9] studied the effect of water cooling on dissimilar welding and concluded that stir zone showed much smoother interface and less intermixing.

The temperature distribution is very important phenomena in deciding the different zones of weld-plate. During experimental work, the temperature is measured with the help of thermocouple, but the temperature of stir zone or thermo-mechanical affected zone could not be measured because of limitations in placing the thermocouples. Thermal numerical simulation provides a very effective tool for predicting the temperature of these zones. Therefore, researchers are focussing more on numerical simulation using finite element analysis software to characterize the thermal effects in different zones in FSW. Schmidt et al. [10] studied and established a model for heat generation based on the different assumptions of contact condition between plate and shoulder surface. Hongjun et al. [11] studied thermo-mechanical model and presented a methodology for predicting transient thermal and mechanical response. Armansyah et al. [12] worked on temperature distribution in friction stir welding using Altair Hyper Works and compared the simulated results with experimental.

Literature reveals that most of experimental and simulation work is done in the area of friction stir welding in natural conditions and there is not much work reported on underwater simulation. Water can decrease the heat affected zone and soften of material, which can increase the weld strength. Water has a high convective heat transfer capacity which can absorb excess heat generated during welding. This process is widely used in fabrication and repair of ships, submarine, oil transporter tank etc. Thus, the objective of the present work is to study the effect of ambient operating conditions on temperature change and the stresses generated in the plates during FSW involving two thin plates of aluminium Al 1050. The considered ambient is air and water by including the effects of convective heat transfer coefficients in numerical analysis. The simulation is conducted using COMSOL Multiphysics software. Results for transient temperature change and generated thermal stresses are obtained and analyzed.

2. Theory and numerical analysis

Figure 1 shows the schematic of FSW process and the related different thermo-mechanical zones. The total heat ($Q_{\text{total}}$) generated during FSW constitutes of heats generated by the friction at shoulder surface ($Q_{\text{sh}}$), tool pin side surface ($Q_{\text{pin}}$) and pin tip surface ($Q_{\text{tip}}$) given as: $Q_{\text{total}} = Q_{\text{sh}} + Q_{\text{pin}} + Q_{\text{tip}}$.

$$Q_{\text{sh}} = 2\pi \tau (R_s^3 - R_{\text{pin}}^3)$$  \hspace{1cm} (1)

$$Q_{\text{pin}} = 2\pi \omega \tau R_{\text{pin}}^2$$  \hspace{1cm} (2)

$$Q_{\text{tip}} = \frac{2}{3} \pi \omega \tau R_{\text{tip}}^3$$  \hspace{1cm} (3)

![Figure 1. Schematic diagram of friction stir welding](image-url)
where, $\omega$ is angular rotation speed and $\tau = \mu P$ is shear stress generated at tool/shoulder surface, $\mu$ is the coefficient of friction and $P$ is the applied contact pressure. $R$ is the radius of different tool sections.

Numerical analysis was performed using commercial finite element analysis software COMSOL Multiphysics V5. From probe tool of software temperature variation in the tool is determined and the thermal stresses were obtained from post-processing of results. Figure 2 shows the geometric model of FSW used in the analysis. The welding was performed virtually by a tool travelling at a speed of 1.75 mm/s on two rectangular aluminium Al-1050 plates each of size 120x60x3 mm. The tool is made of mild steel with geometric properties: $R_{sh} = 10$ mm, $R_{pin} = 3$ mm and tip height $H_{pin} = 2.7$ mm. The tool pin is cylindrical. The welding was done at spindle rotation $\omega = 1200$ RPM with an applied force of 25 kN. The edges of the plates were fully constrained to prevent any motion. Different boundary conditions of convective medium were applied. The convective heat transfer coefficient is taken as 2000 W/(m²K) [13] for water and 15 W/(m²K) [14] for air.

![Figure 2. Geometric model of AA 1050 aluminium plates used in numerical analysis](image)

3. Result and discussion

Figure 3 presents the temperature distribution during welding in case of water and air. The maximum temperature is more in case of air which is around 900 K, while in water it is around 700 K.

![Figure 3. Temperature distribution in aluminium plates in air (left) and underwater (right) conditions](image)
The temperature is less in case of water as excess heat is absorbed by water due to its high convective heat transfer coefficient [4,15]. Water cannot reach below the tool shoulder hence the temperature is more concentrated in this area. Due to high heat absorbing capacity of water there is decrease in peak temperature of weld which decreases the softening phenomena, resulting in enhanced mechanical properties. [6-7].

Figure 4 presents the variation in temperature of different parts of the tool. In tool, pin side will attain maximum temperature in both cases of the operating conditions. It gets heat from flux generated due to tool shoulder, heat due to its own friction and due to plastic deformation. Tool shoulder will always have minimum temperature due to direct contact with convective medium. Figure 5 shows the top view of stresses distribution in aluminium plates. Stresses distribution is mainly dependent on the thermal cycle. This cycle is highly affected by cooling medium as excess heat is absorbed by this medium. The maximum stress in concentrated around the tool pin where the plastic deformation occurs. From the figure 5, we can conclude that aluminium plates have less thermal stresses in case of water [4,14].

![Figure 4. Temperature variation in FSW tool in air (left) and underwater (right) conditions](image)

In case of water, the maximum stress below the tool shoulder is about 786 MN/m² while in air it is around 1042 MN/m². Initially the stresses generated are almost same in both cases. But when there is a significant rise in temperature heat absorbed by water will be more resulting in less thermal stresses compared to air. The maximum value of thermal stresses in plates was found to be about 270 MN/m² in case of air and around 90 MN/m² for water.

![Figure 5. Thermal stresses in weld plates in air (left) and underwater (right) conditions](image)

4. Conclusion
This study investigated the effect of performing FSW process in air and underwater ambient conditions using COMSOL Multiphysics. The frictional heat generated and its flow to different tool parts was also studied. Temperature and thermal stress distributions in plates were obtained. Results
showed that compared to the maximum temperature of about 900 K obtained in air, the temperature of about 700 K was found during underwater FSW. Further, it was found that the maximum stress below the tool shoulder in underwater friction stir welding was around 25 percent less as compared to air. By using water as the convective medium excess heat was absorbed. It resulted in less heat affected zone and less thermal stresses. Thus, we can conclude that underwater FSW is better and can improve thermo-mechanical properties.

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