Researching on hybrid friction stir welding between two differential materials as steel and aluminium

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ABSTRACT
Friction stir welding exploits its solid state process behaviour to join aluminium to steel, which differs in thermal and mechanical properties, and where combination of these metallic alloy by fusion welding prompts a deleterious reaction as a result of the melting and resolidification phases. Recently, hybrid techniques have been employed in FSW for several materials and alloys, particularly for steel–steel joining. These methods are general lyaimed to pre-heat the steel plate materials. This study presents conducted heat simulations and experimental joining flat-plate of aluminum alloy 6061 and SUS 304. Temperature is simulated by the COMSOL software in three states: (1) Preheat the Friction Stir Welding (FSW) by TIG welding, (2) Thermal contact resistance between aluminum and steel, and (3) The welding process using string friction is simulated. The simulations intended to predicting the temperature which is used for preheat and welding process to ensuring the required solid-state welding. The temperature is also determined and checked by a thermal imager comparing with simulation results. Besides, the results of tensile strength is carried out. The Box–Behnken method is used to identify the relationship between the welding parameters (rotation, speed and offset), temperature and tensile strength. The maximum tensile strength is 77% compared to the strength of aluminum alloy. The optimal set of parameters for the process is n = 676 rpm, v = 46 mm / min and x = 0.6 mm. The optimizing welding parameters to achieving good quality of welding process are described. SEM images to determine some properties of welding materials. This is also the basis for initial research to identify some defects in welding of two different materials (IMC thickness and interconnected pores) and the cause of these defects.

Key words: Comsol Multiphysics, intermetallic compound, TIG welding, friction stir welding, dissimilar material

INTRODUCTION
Friction stir welding has been considered to be the most significant development in metal joining in recent decades and, in addition, is a “green” technology due to its energy efficiency, environmental friendliness, and versatility. Friction stir welding produces higher strength, longer fatigue life, lower distortion, less residual stress and essentially defect-free joints compared to arc welding. Numerous demands to use lightweight structures, durable and variety of materials, requires the development of reliable and efficient machining methods. Friction friction welding methods meet the above requirements. One of the most difficult pairs of materials to be welded is between aluminum alloy and steel. There is a great difference in mechanical properties, because Intermetallic Compound (IMC) in traditional weld damage or rapid destruction when the force. FSW is a solid state welding process so it has advantages compared to conventional welding methods. Not only can the problems of solidification be avoided, but it can also limit the formation of IMC, so FSW becomes a solution for welding of different materials.

Recently, hybrid techniques have been used in FSW for some materials and alloys, especially for steel. These methods are generally used to preheat the material before welding (preheat). This activity will soften the material and enable better flow. Luo et al. performed preheat FSW experiments by resistance of magnesium alloy (AZ31B) (similar welding), Al alloy (AA7075) and steel (dissimilar welding). Merkleinand Giera uses lazer to heat the front area of the FSW tool. This technique can increase the possibility of steel deformation and reduce tool wear. The weld strength of the AA6016-T4 with DC04 FSBW steel can reach 80% compared to aluminum alloy. The results show that the rotational speed of 2000mm / min for high weldability. In addition, research has shown that no compound is found. They for achieving good welding results related to the increase in material flow of steel. However, using hybrid techniques in the FSW process requires additional equipment, which increases costs. Compared to other welding methods, FSW is less costly and can easily be welded.

Heat directly influences the formation of IMC, material flow, force welding simulation predicts the amount of heat generated during welding is essential. Especially for different materials, it becomes important to consider the ratio between the contact surface of the plates and the tool. When dissimilar welding materials, if the tool is placed in a part of the material, it produces a high temperature, causing the material to melt. The analysis is quite complex when it comes to the heat generation and temperature distribution in FSW when welding different materials. Two different materials have different properties: temperature, coefficient of friction and plasticity. All of these affect heat generation, temperature distribution.

METHOD

GEOMETRY AND MESH

FSW geometry and analysis is done on the Comsol software. Simulation models are made on aluminum alloy 6061 and 304 stainless steel, 200 mm in length, 75 mm in width and 5 mm thick. Simulation through 3 stages:

- TIG welding, simulation depends on time. The TIG solder is mounted on 304 stainless steel, using the TIG welding, simulation depends on time. The TIG solder is mounted on 304 stainless steel, using the abbreviation and Acronyms.
- Thermal Contact Resistance, simulation depends on time. Normally, the two materials are contact surface. However, upon closer inspection, that many materials have a surface roughness measurable at the micron or nanometer scale surface roughness introduces gaps between contacting materials, which are usually filled with air. The thermal conductivity of gases, such as air, is typically much lower than the conductivity of common solid materials. Therefore, the heat flux due to conduction is smaller in noncontacting regions, leading to increased thermal resistance at the interface.
- Friction stir welding, temperature friction welding process by the shoulder and pin of the tool cause the shoulder diameter is 20 mm and the pin is 6 mm). The drawback of the model is that it does not describe the angle of application and the profile of the shoulders – pin (only cylindrical description).

Mathematical model

Heat TIG welding:

Initial Condition

\[ Q_0 = \frac{nEI}{V} \]  

Where E is voltage, I is welding current, \( v \) is the welding speed and \( \eta \) is the arc efficiency.

Spatial Distribution \( \frac{1}{2} \):

\[ Q_1 = Q_0 e^{-\frac{(x-x_0)^2}{a^2}} \]  

Time Domain Distribution \( \frac{1}{2} \):

\[ Q = Q_1 e^{-\frac{(y-y_0)^2}{b^2}} \]  

Where \( y = vr \), \( r_s = \sqrt{r^2 - (y-y_0)^2} \), \( x_0 \) determines the weld bead centre and \( y_0 \) the weld torch centre.

The physical and realistic model of preheat by TIG welding in Figures 1 and 2.

Thermal contact resistance:

At the contact interface (Figure 3), the thermal contact conductance \( h \) is expressed

\[ h = h_{constriction} + h_{gap} \]

\[ 1 = 1.25k_{mic} \left( \frac{P}{M_{gap}} \right)^{0.95} + k_{gap} \gamma_{gap} \]

Where \( P \) is the contact pressure, \( H_{mic} \) is the microhardness, \( \sigma \) is the surface roughness, and \( m \) is the roughness slope, \( k_{gap} \) is gap conductivity, \( Y \) is micro distance between mean planes, \( V \) is gas rarefaction parameter.

c. Heat friction stir welding

\[ q_{pin}(T) = \frac{\mu}{\sqrt{1 + \mu^2}} r_p \omega T(T) \]  

Where \( \mu \) is the friction coefficient, \( r_p \) is the pin radius, \( \omega \) is the pin’s angular velocity (rad/s) and \( T(T) \) is the average shear stress of the material, shear stress is a function of the temperature. This function with an interpolation function determined from experimental data.

\[ q_{shoulder}(r,T) = (\mu F_s/A_s) \omega r (T < T_{melt}) \]

\[ q_{shoulder}(r,T) = 0 (T \geq T_{melt}) \]

Where \( r \) is the shoulder radius, \( F_s \) represents the normal force and \( A_s \) is the shoulder’s surface area, \( T_{melt} \) is melting temperature.

SIMULATION RESULTS

Heat TIG welding and thermal contact resistance

Determined input parameters of the TIG welding to ensure that when the welding speed changed, the original heat was still constant (because the TIG welding was fix with the milling head, the speed of preheat depends on the welding speed).

Simulation results as shown in Figure 4 show the center temperature of about 775°C. Due to convection and radiation, temperature in the stainless steel area at the back of the TIG welding center is 50 ° 100 mm, about 200 ° 300°C and the aluminum side is about 150°C. Take these two temperatures as input conditions for simulating friction stir welding.

The isotherm in the simulated fracture is caused by the heat transfer between two discontinuous plates.
(Thermal contact resistance) and two different materials with different thermal properties causing the above phenomenon Figures 4 and 5.

**Heat TIG welding and thermal contact resistance**

- Temperature field is disproportionate, due to the differences in material properties, Figures 6 and 7.
- Temperature near the shoulder area is higher than the temperature below the plate.
- Temperature at the center of welding from $500 \div 600^\circ$C. At this temperature, the aluminum alloy is in the hot deformation zone (greater than $0.7T_m$) and the steel is in the warm deformation zone (greater than $0.3T_m$). The area around the instrument temperature from $200 \div 500^\circ$C, depending on the location.
The temperature at the center of welding depends on the speed of rotation, the welding velocity and offset. In particular, rotational speed is the main factor affecting the welding temperature, Figure 8. But because the tool movement is still small (from 0.2 ÷ 0.6), the impact is not much.

EXPERIMENTAL RESULTS AND DISCUSSION

Test Tensile strength

The equipment and tool welding used for experiments (Figures 9 and 10). After welding, the welding samples are processed by wirecut electric discharge method, Figure 11. Test tensile strength of all samples, the result is Table 1.

Box-Behnken method is used to determine the relationship between welding parameters (rotation, speed and offset), and temperature, tensile strength. Regression equation: \( Y = -887.95 + 2.25n + 22.501v - 527.6x - 0.00139n^2 - 0.2176v^2 - 3.75x^2 - 0.01139nv + 0.258nx + 8.85vx \)

The speed (v) and rotation (n) have an effect on the welding strength higher than offset, Figure 12. Figure 13 indicates the changing response surface at the offset is \( x = 0.6 \) mm. The results show that the tensile strength increases with the rotational speed (n) of \( 600 ÷ 750 \) (rpm) and the welding speed (v) \( 40 ÷ 50 \) (mm / min). If the rotation speed (n) and welding velocity (v) are below this level, the tensile strength decreases. The elliptic envelope model clearly shows the above parameters. Therefore, the optimal tensile strength for tensile strength is \( n = 700 \) (rpm) and \( v = 45 \) (mm / min).

Figure 14 indicates the changing response surface at the offset is \( x = 0.4 \) mm. The optimal value for ten-
Figure 8: Main effects plot for temperature.

Figure 9: Tools used for experiments SKD11.

Figure 10: VP-3000 CNC milling machine

Figure 11: Photograph of tensile samples
Figure 12: Main effects plot for tensile strength mean.

Figure 13: Response surface and contour plots that represent the effect of rotational speed and transverse speed, and their interaction on shape conformity when the offset is 0.6 mm.

Figure 14: Response surface and contour plots that represent the effect of rotational speed and transverse speed, and their interaction on shape conformity when the offset is 0.4 mm.
Table 1: Experimental results

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<th>No</th>
<th>Rotational speed (rpm)</th>
<th>Transverse speed (mm/min)</th>
<th>Offset (mm)</th>
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<tr>
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<tr>
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</table>

When the speed of rotation (n) and welding speed (v) are too high or too low, the tensile strength will not be suitable.

Figure 15 indicates the changing response surface at the offset is x = 0.2 mm. Surface texture is more or less the same as x = 0.4 mm. The optimum values of rotational speed and weldability are 700 (rpm) and 37 (mm / min), respectively.

Parametric optimization is related to the properties of the result. Therefore, the optimal condition produces the greatest value (better is better) for the result.

After optimizing experiment parameters with the following parameters: n = 676 rpm, v = 46 mm / min and x = 0.6 mm, Figure 16. We have Test Tensile strength result $\sigma_t = 238.17$ MPa, Figure 17. The welding parameters are optimized to achieve good weld quality and maximum tensile strength is obtained by 77% compared to aluminum alloy Aluminum strength.

Analysis and observation of joint cross-sectional microstructure

Porous flaws (Figure 18) occur on the diffuser side of the diffuser. IMC thickness affects the strength of the weld. Specifically, the weld with IMC about 7 $\div$ 15 $\mu$m (Figure 19) has a low tensile strength of 197Mpa, thick IMC welds become brittle. When the IMC thickness is 2.5$\mu$m, the weld strength is improved (Figure 20), this specimen is re-welded after parameter optimization.

CONCLUSION

Use Box - Behnken method for experimental planning. The maximum tensile strength is 77% compared to the strength of aluminum alloy. The optimal set of parameters for the process is n = 676 rpm, v = 46 mm / min and x = 0.6 mm.

Based on the theory used to simulate the process of preheat, thermal contact resistance and friction welding. Incorporate these theoretical foundations into the COMSOL software for simulations. The initial results show that the heating temperature is about 200 $\div$ 300$^\circ$C for steel and from 100 $\div$ 150$^\circ$C for aluminum, the temperature at the center of welding is from 500 $\div$ 600$^\circ$C and the area around the instrument temperature from 200 $\div$ 500$^\circ$C. Prove that the asymmetric temperature is through the solder joint. The temperature near the shoulder area is higher than the plate bottom temperature. The temperature at the center of welding depends on the speed of rotation, the welding velocity and the amount of displacement.
In particular, rotational speed is the main factor affecting the welding temperature.

SEM images to determine some properties of welding materials. This is also the basis for initial research to identify some defects in welding of two different materials (IMC thickness and interconnected pores) and the cause of these defects.

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**ABBREVIATIONS**

FSW: Friction Stir Welding  
IMC: Intermetallic Compound
Figure 18: Test Tensile strength results of the weld after optimization

Figure 19: Test Tensile strength results of the weld after optimization

Figure 20: Test Tensile strength results of the weld after optimization.
TIG: Tungsten Inert Gas

CONFLICT OF INTEREST

The authors have guaranteed that they have no conflicts of interest to declare.

AUTHOR’S CONTRIBUTION

Truong Minh Nhat are responsible for processing experimentations, collecting and handling datas, and writing all manuscripts as well as final articles. Tran Trong Quyet are responsible for processing experimentations and collecting datas. Truong Quoc Thanh are responsible for controlling and checking articles. Luu Phuong Minh are responsible for identifying and consulting all manuscripts as well as final articles.

REFERENCES


