Thermo-Mechanical Simulation of Temperature Distribution and Prediction of Heat-Affected Zone Size in MIG Welding Process on Aluminium Alloy EN AW 6082-T6.

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Abstract. Welding process is considered as a thermal-mechanical-metallurgical coupled problem. In this study, finite element method (FEM) is adopted for predicting the temperature history in Metal Inert Gas (MIG) welding of 5mm thick aluminium 6082 alloy. The Goldak’s double ellipsoidal moving heat source model was used to analyse the influence of peak temperature to the radial distance from the center of the heat source and the thickness of the plate. Temperature-dependent thermal properties of aluminium alloy 6082 in T6 condition and the convective and radiative boundary conditions were included in the model. The finite element code, ANSYS along with APDL command subroutines was employed to obtain the numerical results. The effect of heat input and welding speed on the weld pool shape and temperature distribution were investigated. Finally, the predicted temperature distribution and the size of heat-affected zone were compared with the experimental results. The comparison shows that they are in good agreement.

1. Introduction
Without doubt, the continued development of aluminium can be primarily attributed to this material’s many desirable physical characteristics, which are comparatively light weight, high strength, versatility of both extruding and casting, and excellent corrosion resistant. In conjunction with the continually developing environmental issues, the superior recycling capability of aluminium makes it an excellent choice for a wide variety of applications. With increasing demand of aluminium in engineering field, the development of aluminium welding technology is undeniably evolved to improve the structural integrity of aluminium alloys itself.

One of the most severe challenges in aluminium welding is the occurrence of heat-affected-zone (HAZ), which may results in a significantly reduced strength compared to the base metal. Principally, during welding, aluminium properties change in the zone adjacent to the weld seam. This change occurs due to the introduction of heat to the base metal which revokes the treatment of certain alloys. This phenomenon, which also known as softening, is significant factor in the heat-treatable alloys particularly in 6000 and 7000 series, and in 5000 series alloys in a work-hardened temper condition. In case of the 6000 series alloys, the heat dissipation during welding can locally reduce the parent metal strength on the order of 30% - 50% and the HAZ normally extends between 10mm-30mm from the centre of the weld [1-3]. However, according to Eurocode 9 [4], the extent of this zone depends on the welding method.
(either Metal Inert Gas (MIG) or Tungsten Inert Gas (TIG)), element thickness, alloying elements and temper designation, while the severity is largely a function of the parent metal used.

Some studies have been focused on prediction of the HAZ of welded joint by using numerical simulation technique. Bjorneklett et al. [5] developed a multi-scale modeling approach where precipitate revolution of Al-Mg-Si alloys can be predicted through finite element simulation. A constitutive model based on microstructure evolution enables realistic prediction of structural performance of aluminium alloy during age-hardening, welding and post weld treatment process. Hori [6] was investigating the effect of HAZ on the joint strength of Al-Mg-Si alloy experimentally. Recently, Dorum et al. [7] presented finite element analyses of plastic failure in the HAZ of 6060 aluminium alloys. The welded connection was modeled using shell elements, solid elements and cohesive-zone elements. The ductility of the welded joints can be estimated with coarser meshes. In this study, a numerical model to predict temperature distribution and the width of HAZ was proposed. The obtained numerical results were compared with experimental data. It can be used in practical simulations of MIG welded aluminium alloy connections to reduce the need of extensive mechanical testing, particularly in mapping the width of HAZ.

2. Experimental procedure

The experimental setup consists of a MIG welding system and a 6-axis high precision robot arm as shown in Figure 1. The welding machine Kemppomat 2500 was used to perform the single-sided welding of T-joint. The robotic arm KUKA KR6 was used to control the welding speed and assist the welding torch along the path with constant distance and angle. The distance of contact tip was maintained at 5mm and the torch angle was 30° inclined from horizontal base specimen. A single pass welding was performed with the presence of pure Argon (99%) as shielding gas to protect the molten pool from atmospheric contamination. The gas flow rate was set at 20 liter/min. A consumable filler of AA 4043 with diameter of 1.2 mm (~ 5% Si) was used in this welding process due to the ability of reducing crack sensitivity. The wire feeding rate was set to 6.5 m/min. During the welding process, welding speed and voltage input were varied; only current input is kept constant. All process parameters were chosen based on preliminary test results and presented in Table 1.

| Table 1. The process parameters for MIG welding experiment |
|-----------------------------------------------------------|
| Argon flow rate (l/min), \( f \)                          | 20  |
| Torch angle (deg), \( \alpha \)                           | 30° |
| Distance of contact tip (mm), \( d \)                     | 5   |
| Wire feeding rate (m/min)                                 | 6.5 |
| Diameter of welding wire (mm)                            | 1.2 |
| Welding current (A), \( I \)                              | 250 |
| Welding speed (m/min)                                    | I   | II  | III | IV |
| Voltage (V)                                               | 0.35 | 0.4 | 0.45| 0.5|
|                                                          | 23.0 | 25.5| 28.3| 31.4|

The material used in this study is aluminium alloy EN AW 6082 in T6 condition. The welding coupons were cut by an abrasive water-jet cutting system with the dimensions of 120 mm x 120 mm x 5 mm and 120 mm x 60 mm x 3mm. The 5 mm-thickness plate was selected to be the base material, whereas the 3 mm-thickness plate was used as the flange material with designed bevel of 45° to ensure full penetration of the weld seam. The flange material was tightly clamped, 90° from the base material and a zero gap was assumed to be achieved. A thermal imaging camera FLUKE Ti32 was used in this analysis to record the temperature history during the welding process.
3. Numerical model of thermal analysis

The simulation of thermal analysis during MIG welding process requires a three-dimensional modeling. In this context, the ANSYS non-linear finite element code is adopted due to its flexibility in modeling and its capability in obtaining full field numerical solution. The input files, written in APDL command language of the finite element code, have been inputted for analysis runs and thermal load is applied in time steps, thus defining the analysis as transient. In order to accurately capture the occurring phenomena during thermal cycle, the graded-mesh construction is used for the analysis. This approach is based on a dense mesh division along the weld line and its adjacent zone. The mesh size became coarser as the distance from the weld bead zone increase. It was constructed primarily of solid hexahedral element SOLID70, except in transition areas of thin to coarse mesh, where the tetrahedral SOLID87 element is required.

To reduce the computational time, only half of the actual length and width of specimen was taken into account throughout the analysis. Figure 2(a) and (b) show the considered model of T-joint profile for the analysis and the mesh density transition for the model respectively. A sequence of convergence tests has been conducted to select suitable element size particularly in the thickness direction and at the region near the weld line. Several levels of meshes with varying element numbers from 200,000 to 500,000 in scales of width, length and thickness are chosen to determine the effect of element size on the convergence of computations. The simulated peak temperature became independent on the mesh density of 350,000 elements as shown in Figure 3. Therefore, a mesh of over 350,000 elements is employed to the model. Nearby and along the weld bead area, the chosen element size is 0.0005, whereas element size of 0.005 is employed in the coarser region. A free mesh is used in order to connect these two regions.

Figure 1. (a) Experimental setup. (b) Schematic diagram of experimental setup

Figure 2. (a) T-joint profile for thermal model analysis. (b) Mesh density transition of thermal model.
3.1 Model assumptions
In building the model and reasonably simplify the finite element thermal analysis, the following assumptions were introduced:

1) The initial temperature of the model is initially at 25°C.
2) The density of aluminium alloy 6082 is taken to be 2770 kg/m³, while the thermal properties of the material such as conductivity and specific heat capacity are temperature dependent as shown in Figure 4.
3) The fluid flow in the molten pool is neglected.
4) The heat input of welding process obeys the Gaussian distribution of double ellipsoidal heat source model, which was presented by Chen et al. [8].
5) Convection effect is considered.
6) A full penetration depth is assumed and weld seam is incorporated as part of the model.
7) The welding efficiency is taken to be 0.75 [9-12].

3.2 Governing equations and heat source model
The fundamental behavior of heat conduction in the bond area is an energy flux that flows from a hot region to a cooler region, which linearly dependent on the temperature gradient, $\Delta T$.
\[ Q = -k \Delta T \]  

(1)

where \( k \) is the thermal conductivity in W/mK. It should be noted that the minus sign is necessary due to the direction of the heat transfer to the decreasing temperature. The specific heat, \( c \), can be expressed as the required energy in order to have a temperature gradient in the specimen. Hence, the conservation of energy is expressed in a differential form in terms of thermal flux, specific heat and a distributed volume heat-source in the Cartesian coordinate system. The governing differential equation for transient thermal analysis can be expressed as [14]:

\[
\rho c_p \frac{\partial T}{\partial \tau} = \frac{\partial}{\partial x} \left( k_x \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left( k_y \frac{\partial T}{\partial y} \right) + \frac{\partial}{\partial z} \left( k_z \frac{\partial T}{\partial z} \right) + \dot{q}
\]

(2)

where \( \rho \) is the density of the conducting medium; \( c_p \) is the specific heat of the medium; \( k_x, k_y, k_z \) are the thermal conductivities of the medium in the \( x \)-, \( y \)-, and \( z \)-direction, respectively; \( \tau \) is time; and \( \dot{q} \) is the total heat input based on Goldak’s double ellipsoidal model [15]. To solve the differential equation, boundary and initial conditions are required. The general form of boundary conditions can be written as:

\[
- \left( k_x \frac{\partial T}{\partial n_x} + k_y \frac{\partial T}{\partial n_y} + k_z \frac{\partial T}{\partial n_z} \right) = q_{\text{conv}} + q_{\text{rad}} - \alpha q_{\tau}
\]

(3)

where \( n_x, n_y, n_z \) are the direction cosines of the normal to the surface; \( T_\infty \) is the ambient temperature; \( h_{\text{conv}} \) is the convective heat transfer coefficient; \( \alpha \) is the absorptivity; and \( q_{\tau} \) is the radiant laser heat flux function. The convective heat transfer coefficient was assumed to vary with temperature and defined as:

\[
h_{\text{conv}} = \frac{kN_u}{L}
\]

(4)

where \( k \) is the thermal conductivity of the material, \( L \) is the characteristic length of the surface, and \( N_u \) is the Nusselt number:

\[
N_u = 5.67 Pr^{1/3} Gr^{1/3}
\]

(5)

Here, \( Pr \) is the Prandtl number and \( Gr \) is the Grashof number. Thermal radiation is assumed from the surface to surroundings. Prior to welding, the material is assumed to be at room temperature. The heat losses due to radiation were modeled by Stefan-Boltzmann relation:

\[
q_{\text{rad}} = \sigma_{\text{st}} \varepsilon \tau (T^4 - T_\infty^4)
\]

(6)

where \( \sigma_{\text{st}} \) is Stefan-Boltzmann constant (equal to 5.67 x 10^{-8} W/m²K^4) and \( \varepsilon \) is the emissivity of the surface (\( \varepsilon = 0.05 \)), in accordance to data published by Mikron Verterung of Switzerland [16]. The schematic presentation of applied boundary conditions was illustrated in Figure 5.
The power densities of the double ellipsoidal ellipses, that comprise a front and a rear quadrant of the heat source as shown in Figure 6, can be stated as:

\begin{align}
q_f(x, y, z) &= \frac{6\sqrt{3}f_fQ}{bca_f\pi\sqrt{\pi}} e^{-\frac{3x^2}{a_f^2}} e^{-\frac{3y^2}{b^2}} e^{-\frac{3z^2}{c^2}} \\
q_r(x, y, z) &= \frac{6\sqrt{3}f_rQ}{bca_r\pi\sqrt{\pi}} e^{-\frac{3x^2}{a_r^2}} e^{-\frac{3y^2}{b^2}} e^{-\frac{3z^2}{c^2}}
\end{align}

(7) \hspace{1cm} (8)

where \(Q\) is the energy input rate, \(f_f\) and \(f_r\) are the fractional factors of the heat deposited in the front and rear quadrant, \(a_f, a_r, b\) and \(c\) are heat source parameters. The heat source parameters are \(a_f = 5\) mm, \(a_r = 20\) mm, \(b = 5\) mm, \(c = 8\) mm and \(f_f + f_r = 2\).
was determined by multiplication of the span length with welding speed. An APDL based subroutine is
written to simulate the moving heat source along the weld line. Figure 7 illustrates the heat distribution
of the heat source model at the top of the welded plate acquired from the simulation results.

Figure 7. Heat distribution of the heat source model acquired from simulation at t = 0.25s (Heat input
= 573.751/mm).

3.3 Thermal modeling
The thermal analysis is focused on the prediction of the heat transfer in the weld pool, the temperature
distribution in the overall weldment, the size of fusion zone (FZ), heat-affected zone and geometry of
the molten pool. The heat-affected zone identification relies upon the experimental data and available
data from open literature by Matusiak [17] and Myhr and Gron [18], with an assumption that the studied
material has an identical chemical composition. From previous studies [19–21], it is evident that the
reversion of hardening precipitates occurring during the welding process, where the peak temperature
range from 220°C to 500°C as depicted in Figure 8(a). However, a large fraction of alloying elements
adjacent to the fusion boundary, undergo natural aging after a period of 5-7 days (Figure 8(b)), resulting
in a slight increase of hardness values due to the enhancement of hardening precipitates. According to
[18] element which experienced a peak temperature of about 220°C and below will recover to its original
hardness (base metal) during the natural aging process. According to this model, the HAZ profile was
categorized based upon the quasi-stationary temperature distribution around a moving heat source.
Therefore, in this study, the HAZ was divided into 2 regions;

1) Sub-HAZ 1, where the range of peak temperature, 430°C < T < Solidus temperature (~545°C).
2) Sub-HAZ 2, where the range of peak temperature, 220°C < T < 430°C.

Aside from those regions (where the range of peak temperature, T < 220°C), the material was assume
to have the base metal characteristics. The weld pool was considered as the fusion zone (FZ) during the
analysis, by assuming that the material was fully melted at solidus temperature (545°C) and the addition
of filler metal will change the Si content in weld zone [22].
The thermal cycle of the process was recorded by the two thermocouples located closer to the weld line. All these data were then compared with the numerical nodal results from nodes of the same coordinates of the thermocouple position. The results were presented in Figure 9. TC1 and TC2 represent the location of thermocouples 10 mm and 20 mm from the center of the weld line. From the figure, the maximum temperatures recorded by both thermocouples have been accurately captured by the simulation model. The measured cooling gradients exhibit almost similar curves with the numerical results of the finite element model. Generally, it can be stated that the developed simulation model was in excellent agreement with the experimental data. The temperature reading for the TC01, which was located closer to the weld line, was recorded the highest value but considered to be moderate in magnitude, since the maximum temperature at 15 mm distance from the weld line was just below 230℃. However, the temperature difference was not very evident even between each thermocouple of TC01 and TC03, at a distance of 15 mm and 25 mm respectively, which have a temperature difference of almost 25℃. This can be attributed to the high thermal conductivity of EN AW 6082, which allow rapid heat dissipation in the bulk of the material. In addition to that, the cooling curve of the thermocouple nearest to the fusion line (TC01) and the thermocouple at 25 mm from the fusion line (TC03) are almost identical. The two curves converge approximately 70 seconds after the arc initiation at 100℃.

Figure 9. Comparison of thermal cycle during MIG welding of EN AW 6082 experimentally and numerically. (Voltage = 25.5 V, current = 250 A, velocity = 0.35 m/min, heat input = 0.819 kJ/mm)

Figure 10 illustrated the comparison of the molten pool shape after penetration during MIG welding process. The picture on the left depicts the obtained weld pool by experiment, and the right
picture illustrates the computed weld pool in terms of the isotherm contour. The region of the molten pool, in which the solidus temperature of the alloy (~545 °C) was exceeded and melting occurred is called the fusion zone. In the left figure, the boundary of the FZ and HAZ was denoted by the dashed white line (fusion line), which also indicates the locus of points whose peak temperature is equal to the solidus temperature. It can be observed clearly here that the FZ exhibit distinctly different microstructural morphology as compared to the adjacent zone. The metallurgical transformation of EN AW 6082-T6 was expected to occur starting from the lower critical temperature of 220°C.

Figure 10. Weld pool profile obtained by (a) experiment and (b) simulation. MIG welding parameters; Current = 250 A, Voltage = 28.3 V, Welding speed = 0.35 m/min

4. Results and discussions

The temperature distribution profiles are compiled for different welding speed and heat input power. In order to evaluate the effect of heat input on the weld pool dimension of MIG welding, a set of simulation case has been studied by varying the input voltage over a constant value of welding speed at 0.35 m/min. Figure 11 presents a comparison of the simulated weld pool shapes made in the case of M1, M8, and M9. Additionally, simulation cases of M2 and M7 were also analyzed to obtain a clear trend of the corresponding effect. The dimension of the HAZ and penetration depth were measured for each simulation cases and compared with the experimental data obtained, as summarized in Table 2. It can be seen that the simulation cases of M7 and M2 gave almost similar results with the corresponding experiment, with the percentage accuracy of almost 90%. The case of M2 and M7 were done for validation purpose because the experimental data were only available for these two cases. Due to the limitation of time and cost, therefore thermal model was used to simulate the other cases (M1, M8 and M9).

Table 2. List of simulation and experimental results of MIG welding for heat input variation (Constant welding speed = 0.35 m/min)

| Case | "Heat input (kJ/mm) | Depth of FZ (mm) | Width of HAZ (mm) |
|------|---------------------|------------------|------------------|
|      |                     | Model | Exp. | % Error | Model | Exp. | % Error |
| M1   | 0.942               | 5.97  | -    | -       | 25.62 | -    | -       |
| M2   | 0.849               | 5.87  | 6.13 | 4.24    | 25.57 | 26.00| 1.65    |
| M7   | 0.690               | 5.32  | 5.92 | 9.14    | 25.21 | 27.00| 6.63    |
| M8   | 0.510               | 4.77  | -    | -       | 23.71 | -    | -       |
| M9   | 0.765               | 5.51  | -    | -       | 25.43 | -    | -       |

*Based on a constant input current of 250 A and efficiency of 0.70.*
Figure 11. Weld pool profile of MIG welding with varying heat input (a) low heat input (0.51 kJ/mm) (b) intermediate heat input (0.76 kJ/mm) (c) high heat input (0.94 kJ/mm)

Figure 12 illustrates the dependency of penetration depth and width of HAZ on the heat input variation. From the figure, it can be seen that the penetration depth and the size of HAZ have the tendency to increase with the increase of heat input. In general, data fitting resulted in a non-linear relation between the depth of fusion zone and the width of HAZ with the heat input variation.

In the case of penetration depth, the depth of FZ was affected by the power density distribution of the heat source. The weld penetration increases with increasing power density [21]. For all simulation cases, the effective radius of the heat source was kept constant. Therefore, as the heat input increases over the same surface area, the power density increases, and consequently increasing the penetration of weld pool. In all simulation cases, the Marangoni effect and recoil pressure were neglected. From the Figure 11, it can be observed that the dimension of the melt pool was almost identical. However, the HAZ width was widening significantly. The melt pool dimension was affected largely by the heat
distribution factor. In contrary, the HAZ width was influenced by the temperature gradient. As the heat input increases, the peak temperature elevates, so does the temperature gradient. Rearranging equation (3) and equation (4), it can be shown that the estimated HAZ size is proportional to the heat input as well as peak temperature (considering the HAZ width in terms of $L$, the characteristic length of the surface) as follow:

$$
\begin{align*}
-\text{Energy} &= h_{\text{conv}}(T - T_{\infty}) + q_r - \alpha q_r \\
-\text{Energy} &= \frac{k N u}{L} \nabla T + q_r - \alpha q_r \\
L &= \frac{-1}{\text{Energy}}(k N u \nabla T + q_r - \alpha q_r)
\end{align*}
$$

(9)

Another attempt of simulation was made in order to understand the effect of welding speed variation on the size of HAZ and penetration depth of weld pool. In these cases, the input voltage remained unchanged (28.3 V), and the welding speed was increased slightly from 0.35 m/min to 0.75 m/min. The results were presented in Figure 13 and Table 3.

![Figure 12. Plots of penetration depth and width of HAZ against heat input variation for MIG thermal model](image)

**Table 3.** List of simulation and experiment result of MIG thermal model for welding speed variation (Constant voltage = 28.3 V)

| Case | Welding speed (m/min) | Depth of FZ (mm) | Width of HAZ (mm) |
|------|-----------------------|-----------------|------------------|
|      |                       | Model | Exp. | % Error | Model | Exp. | % Error |
| $M2$ | 0.35                  | 5.87  | 6.13 | 4.24    | 25.57 | 26.00 | 1.65    |
| $M3$ | 0.45                  | 3.51  | 3.34 | 5.09    | 24.78 | 25.00 | 0.88    |
| $M4$ | 0.55                  | 2.75  | -    | -       | 24.53 | -    | -       |
| $M5$ | 0.65                  | 2.58  | -    | -       | 23.51 | -    | -       |
| $M6$ | 0.75                  | 2.43  | -    | -       | 23.03 | -    | -       |
Figure 13. Weld pool profile of MIG welding with varying welding speed (a) low speed (0.35 m/min) (b) intermediate speed (0.55 m/min) (c) high speed (0.75 m/min)

Figure 14 illustrates the effect of the welding speed variation on the penetration depth and width of HAZ of MIG welding model. From the figure, a clear trend can be observed, in which the welding speed has a substantial effect on the penetration depth and the width of HAZ. Higher welding speed will eventually decrease the penetration depth and width of HAZ.
5. Conclusion
The experimental and numerical analysis of MIG welded aluminium components were successfully conducted in this study. From the results, it was concluded that heat input and welding speed have a significant effect on the penetration depth and size of HAZ. It was found that in most cases the model could yield an almost accurate result with the prediction error of below 10%. In all cases of simulation, the penetration depth and the width of HAZ have the tendency to increase with the increase of heat input. On the other hand, the welding speed has a substantial effect on the penetration depth and the width of HAZ. Higher welding speed will eventually decrease the penetration depth and width of HAZ.

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