Modeling of 3D temperature field in butt welded joint of 6060 alloy sheets using the ANSYS program

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Abstract. In work, the modeling of a three-dimensional temperature field in a butt weld connection of two 6060 aluminum alloy sheets using Finite Element Method is presented. The calculations were performed for two welding methods: TIG (Tungsten Inert Gas) and MIG (Metal Inert Gas). The Goldak's double ellipsoidal heat source model has been used in modeling. The thermal-mechanical properties of the material were assumed to depend on the temperature. The Workbench, DesignModeler, Mechanical, Fluent and CFD-Post modules of the ANSYS program were used for numerical simulations. In the description of the geometry of joints, cube type elements were used, with density of grid in the heat affected zone. The parabolic shapes of face and root were assumed based on the literature and results of the experiment. The temperature distributions in cross-sections of welded joints as well as welding thermal cycles at selected points were analyzed. The results of numerical simulations were verified experimentally. Comparison of calculated and obtained in the experiment the characteristic limits of heat affected zones showed satisfactory compatibility. The directions of heat propagation determined by vectors of cooling rates coincide with the longitudinal axis of dendritic grains determined on the basis of metallographic tests.

1. Introduction

Thermal phenomena are important in the technological processes of metals and their alloys. In many processes, such as casting [1, 2], heat and laser treatment [3, 4], welding [5, 6], welding coatings [7, 8], they are the essence of the technological process, i.e. calling the right temperature is to achieve the desired state of the material leading to a change in the state of focus or its properties. In other processes, the increase of the temperature of the processed material is aimed at determining such properties that enable the final technological method, eg. FSW (Friction Stir Welding) [9], coating [10]. In some processes, thermal effects are a secondary effect, such as in machining [11]. Depending on the material, thermo-mechanical properties change as the temperature changes [12], and in the case of steel (cast steel, cast iron), there are structural changes (phase transformations in solid state).

In modelling the temperature field of welding processes, the selection of the heat source model and the calculation method is very important. The analysis of models of heat sources used in the description of thermal phenomena in welding processes is presented, among others in the works [13, 14]. The first proposals were point heat source models [15, 16]. Because the point models did not allow for describing the temperature field near the weld axis, Eagar [17] proposed a Gaussian distributed surface source. The breakthrough moment was the double ellipsoid model of the heat source proposed by Goldak [18]. Goldak's proposal was the first model taking into account the volumetric nature of the welding source. In work [19] a volumetric model with Gaussian power distribution in the horizontal plane and parabolic change in the vertical direction was proposed.
A further direction of the search was to consider the inclination of the electrode (welding head) in heat source models [20, 21] and to analyze the influence of this inclination on the temperature distribution in welded joints [22, 23].

Because single-distributed models of heat sources only took into account the heat of the welding arc, disregarding the heat transferred to the weld pool through the molten additional material (e.g., electrodes), in works [24-27] two-distributed models were proposed. It allowed, among others, to obtain an irregular line of fusion (often observed in welding practice), impossible to reproduce with the use of single-modal source.

Despite many models and numerous publications on temperature field modelling, intensive search for models and algorithms is still in progress to describe the temperature field enabling to obtain temperature distributions as close as possible to real values [28-33].

In the descriptions of the temperature field during welding, analytical [34, 35], semi-analytical [36] and numerical [33, 37-39] solutions for the differential heat conduction equation are used.

The proposed solutions concern the possibility of describing the temporary temperature field during particular welding methods and related processes: GMAW (Gas Metal Arc Welding) [40, 41], SAW (Submerged Arc Welding) [42-45], GTA (Gas Tungsten Arc) [25], hardfacing [46] and surfacing [47], PAW Plasma Arc Welding) [48], PAC (Plasma Arc Cutting) [49], LBM (Laser Beam Welding) [50], hybrid laser-arc welding [51], hybrid laser-waterjet micro machining [52,53] and metallization [54].

This paper presents modelling of 3D temperature field in butt weld joint of 6060 alloy sheets using the ANSYS program. Numerical simulations have been carried out for two welding methods (GTA and GMA) verified experimentally.

2. Experimental work
Welding tests of single pass butt welded joint of 6060 aluminum alloy sheets were carried out in the Welding Laboratory of Czestochowa University of Technology. Welded joints were made using two methods (in the argon shield):
- GTA method (141) – PN-EN ISO 4063:2011 [55],
- GMA method (131) – PN-EN ISO 4063:2011 [55].

The scheme of single-pass butt welding of aluminum alloy sheets is presented in Figure 1. The chemical composition and thermomechanical properties of has been summarized in Tables 1 and 2.

![Figure 1. The scheme of single-pass butt welding process.](image)

The welding process involved the manufacture of a butt joint of two 6060 aluminum alloy sheets with dimensions 244x110x4 mm by GTA (141) method was carried out on the Faltig 315 welding device (OZAS, Opole, Poland) [56] (figure 2).
Table 1. Thermomechanical properties of Alloy 6060.

| Property                  | Value                      |
|---------------------------|----------------------------|
| Density                   | 2700 (kg/m³)               |
| Specific heat             | 898 (J/kgK)                |
| Thermal conductivity      | 209 (W/mK)                 |
| Solidus temperature       | 610 (°C)                  |
| Liquidus temperature      | 655 (°C)                  |

Table 2. The chemical composition of Alloy 6060 (with accordance with EN 573-1[57]).

| Element | Participation (%) |
|---------|-------------------|
| Mg      | 0.35 – 0.60       |
| Mn      | ≤0.10             |
| Fe      | 0.10-0.30         |
| Si      | 0.30 – 0.60       |
| Cu      | ≤ 0.10            |
| Zn      | ≤ 0.15            |
| Cr      | ≤ 0.05            |
| Ti      | ≤ 0.10            |
| other   | ≤ 0.05            |
| Al      | rest              |

Faltig 315 allows welding with a non-clay electrode (141) and coated electrode (111) direct current and alternating current. The parameters of the 6060 aluminum alloy GTA welding process are shown in Table 3.

Figure 2. Faltig 315 AC/DC. Figure 3. Synermig 400.
The welding process involved the manufacture of a butt joint of two 6060 alloy sheets with dimensions of 200x60x5 mm using the GMA (131) method. The welding process was carried out on the Synergine 400 welding device (OZAS, Opole, Poland) presented in Figure 3. The device is intended for joining construction steels, high-alloy steels of type 18-8 and alloys (AlMg5 and AlSi5) [56]. We can weld with direct current and alternating current. The welding parameters using GTA method is setting in Table 4.

| Parameter                              | Value         |
|----------------------------------------|---------------|
| Current type                           | Alternating   |
| Voltage                                | 15.2 A        |
| Current                                | 130 A         |
| Welding speed                          | 8.6 cm/min    |
| Diameter of electrode                  | 2.4 mm        |
| Composition of additional material     | AlMg5         |
| Shielding gas                          | Ar 4.5        |
| Intensity of shielding gas              | 15 l/min      |

Table 3. Welding parameters during GTA welding.

| Parameter                              | Value         |
|----------------------------------------|---------------|
| Current type                           | Alternating   |
| Voltage                                | 15.2 (A)      |
| Current                                | 130 (A)       |
| Welding speed                          | 8.6 (cm/min)  |
| Diameter of electrode                  | 2.4 (mm)      |
| Composition of additional material     | AlMg5         |
| Wire feeding speed                     | 8.5 (m/min)   |
| Shielding gas                          | Ar 4.5        |
| Intensity of shielding gas              | 15 (l/min)    |

Table 4. Welding parameters during GMA welding.

3. Examples of numerical simulations
The problem of modeling the temperature field in welding processes using the finite element method was made using Ansys packages (4 programs from Ansys software):
- Ansys DesignModeler used to make a solid geometry,
- Ansys Meshing used to divide the solid into finite elements,
- Ansys Fluent used to define the model and calculations,
- Ansys CFD-Post for the development and analysis of results,

Ansys Fluent uses the following equation to solve heat transfer problems for a solid:

\[
\frac{\partial}{\partial t} \left( \rho h \right) + \nabla \cdot \left( \rho \vec{v} h \right) = \nabla \cdot (k \nabla T) + Q
\]

(1)

where: \( \rho \) – density, \( h \) – enthalpy, \( k \) – conductivity, \( T \) – temperature, \( Q \) - volumetric heat source, \( \vec{v} \) - speed field. When modeling the three-dimensional temperature field in welding processes, the dual
ellipsoidal moving heat source proposed by Goldak presented in the figure 4 was used. The Goldak’s model consists of two semi-ellipsoidal volumes that create a heat flux. For points \((x, y, z)\) belonging to the semi-ellipse located in the front part of the source, the heat flux is described by the equation:

\[
q_f(x, y, \xi) = \frac{6 \sqrt{3} f_f Q}{abc \pi \sqrt{\pi}} \exp\left(-\frac{3x^2}{a^2}\right) \exp\left(-\frac{3y^2}{b^2}\right) \exp\left(-\frac{3\xi^2}{c_f^2}\right)
\]

(2)

However, for points \((x, y, z)\) belonging to the back of the source:

\[
q_r(x, y, \xi) = \frac{6 \sqrt{3} f_r Q}{abc \pi \sqrt{\pi}} \exp\left(-\frac{3x^2}{a^2}\right) \exp\left(-\frac{3y^2}{b^2}\right) \exp\left(-\frac{3\xi^2}{c_r^2}\right)
\]

(3)

where: \(a, b, c_f, c_r\) are the parameters of the ellipsoidal heat source, \(f_f, f_r\), proportionality coefficients corresponding to heat in the front and rear parts of the heat source, where \(f_f + f_r = 2\), \(\xi\) distance of current source position to point \((x, y, z)\) [18].

![Double ellipsoidal Goldak’s model of heat source.](image)

**Figure 4.** Double ellipsoidal Goldak’s model of heat source.

Boundary Conditions:

- First-type boundary condition (Dirichlet):
  \[T_s = f(x, y, z, t)\]

(4)

- Second-type boundary condition (Neumann):
  \[q_s = -k \frac{dT(x, y, z, t)}{dx}\]

(5)

- Convection boundary condition:
  \[q_{\text{conv}} = h(T_{\text{free}} - T_w)\]

(6)

- Radiative condition:
  \[q_{\text{rad}} = \varepsilon \sigma (T_{\text{ref}}^4 - T_w^4)\]

(7)
3.1. **Modeling of the temperature field during butt welding of 6060 aluminum alloy sheets using the GTA method (141).**

![Finite element mesh for temperature field modeling during GTA welding.](image)

**Figure 5.** Finite element mesh for temperature field modeling during GTA welding.

| Arc power 1970 [W] | Efficiency |
|-------------------|------------|
| Heat transfer coefficient [W/m²K] | Speed of welding [m/s] | External emissivity |

| GTA | 0.6 | 25 | 0.0014 | 0.1 |

![Temperature distribution during welding of Al6060 alloy sheet with the GTA method at time t = 69 s from the beginning of welding in the cross-section.](image)

**Figure 6.** Temperature distribution during welding of Al6060 alloy sheet with the GTA method at time $t = 69$ s from the beginning of welding in the cross-section.

The cross-section shows the temperature distribution at time $t = 69$ s from the beginning of welding. The graph shows the temperature change with the change of distance from the heat source. It may observe a sharp drop in temperature in the initial phase of the graph, which presents densely arranged isotherms near the source. Figure 7 shows two points for which a diagram of thermal cycles was performed during the time of connecting the two butt-welded alloy plates using the GTA method.
The results obtained give satisfactory results. The red color on the left is the area in which we obtained a temperature above solidus where the material melts. The dimensions of the remelting zone obtained during modeling in relation to experimental studies show divergences less than 5%.

Figure 8. The remelting zone when modeling the temperature field when GTA welding (141) compared to the experimental study (metallographic fracture).

3.2. Modeling of the temperature field during butt welding of 6060 aluminum alloy sheets using the GMA method (131)
During the modelling of the temperature field during the butt welding using the GMA method, two sheets of 6060 alloy, the solid was divided into 444609 cubic elements and 487760 nodes with a densegrid in the joint area [57].
Figure 9. Finite element mesh for temperature field modeling during GTA welding.

Table 6. Parameters used in the simulation.

| Arc power 1970 [W] | Efficiency 0.6 | Heat transfer coefficient 25 [W/m²K] | Speed of welding 0.0014 [m/s] | External emissivity 0.1 |
|-------------------|----------------|--------------------------------------|-------------------------------|------------------------|
| GTA               | 1970           |                                      |                               |                        |

Figure 10. Temperature distribution during welding of Al6060 alloy sheet with the GMA method at time t = 24 s from the beginning of welding in the cross-section.
Figure 11 shows two points for which a diagram of thermal cycles was made during the joining of two butt-welded alloy plates using the GTA method.

The result of numerical simulations gives satisfactory results. The red color on the left shows the area in which we reached the temperature above the solidus where the material melts. The difference in dimensions obtained in the simulation with respect to experimental tests is below 5%.

4. Conclusion
Numerical simulations of the temperature field in welding processes for sheets made of aluminum alloys:
- butt welded joint made with the GTA method (using a infusible (tungsten) electrode in the Argon shield with the addition of a deposited metal in the form of a wire),
- butt welded joint made with the GMA method (using a fusible electrode in the Argon shield), allowed to determine the fusion zone of welded sheets in the mentioned processes.
The numerical simulation results were verified experimentally by comparing the shapes and dimensions of remelting zones obtained theoretically (computationally) and experimentally (on the basis of metallographic specimen).

The obtained results are the origin point for the calculation of strain and stress states in the welding processes considered in the article.

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