Numerical analysis of thermal phenomena during surface heat treatment of AlZn5.5MgCu aluminum alloy by GTA welding method

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Abstract. In work, the modelling of a three-dimensional temperature field during surface modification of AlZn5.5MgCu aluminum alloy using GTAW (Gas Tungsten Arc Welding) technology is presented. GTAW is widely used for making welded joints using additional material (filler material). In the analyzed process, no additional material was used, and the effect of heat treatment was obtained by directly applying the electric arc to the surface of the material. The calculations were performed using Finite Element Method. The Goldak's double ellipsoidal heat source model has been used in modelling. 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 element heat treated, cube type elements were used, with density of grid in the heat affected zone. The temperature distributions in cross-sections of heated element 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 fusion lines showed satisfactory compatibility.

1. Introduction
Welding methods are used not only to connect elements made of metals and their alloys, but also to improve the surface of these elements by heat (laser) treatment [1, 2] or by applying coatings [3–10]. The GTA (Gas Tungsten Arc) welding method without the use of additional material is often used for welding joints. In work [11] and patent [12], the authors were proposed to use this method in inert gas shielding for surface heat treatment of AlZn5.5MgCu aluminum alloy sheets. This paper presents a thermal phenomena analysis during this process and compares it with the results of experimental tests.

2. Experiment
Experimental tests of surface treatment of 7075 aluminum alloy were carried out in the laboratory of the Częstochowa University of Technology. The machining was performed by the GTAW (142) method [13] for 4 different passage welding velocities (figure 1).

Diagram of the surface treatment process of aluminium alloy sheet is shown in figure 2. Tables 1 and 2 present chemical composition [14] and thermo-mechanical properties [15] of the aluminum alloy AlZn5.5MgCu.
Welding speed

1 pass – 20 cm min\(^{-1}\)

2 pass – 40 cm min\(^{-1}\)

3 pass – 50 cm min\(^{-1}\)

4 pass – 60 cm min\(^{-1}\)

**Figure 1.** Machining macroscopic effect, pass 1–4.

**Figure 2.** Scheme of the GTAW surface treatment process.

| Table 1. The chemical composition of Alloy 7075 (with accordance with EN 573-1 [14]). |
|-----------------------------------------------|
| **Element** | **Participation (%)** |
| Mg          | 2.1–2.9                |
| Mn          | ≤ 0.3                  |
| Fe          | 0.1–0.5                |
| Si          | 0.0–0.4                |
| Cu          | 1.2–2.0                |
| Zn          | 5.1–6.1                |
| Cr          | 0.18–0.28              |
| Ti          | ≤ 0.2                  |
| Zr          | ≤ 0.25                 |
| Other       | ≤ 0.05                 |
| Al          | Rest                   |

**Table 2.** Thermomechanical properties of Alloy 7075 in 26 °C [15].

| Property                  | Value               |
|---------------------------|---------------------|
| Density                   | 2810 (kg m\(^{-3}\)) |
| Specific heat             | 860 (J kg\(^{-1}\) K\(^{-1}\)) |
| Thermal conductivity      | 130 (W m\(^{-1}\) K\(^{-1}\)) |
| Solidus temperature       | 480 (°C)            |
| Liquidus temperature      | 640 (°C)            |
The surface treatment process was carried out on a 70×100×15 mm aluminum alloy plate using the GTAW method (142). The test was performed using the FALTIG 315 AC/DC welding device (OZAS, Opole, Poland) [16] shown in figure 3. The treatment was carried out with direct current with positive polarity, using a tungsten electrode with ThO$_2$ and welding parameters set in table 3.

![Figure 3. Faltig 315 AC/DC.](image)

**Table 3. Welding parameters during GTA welding.**

| Parameter          | Value |
|--------------------|-------|
| Current type       | Direct|
| Voltage            | 15.2 A|
| Current            | 130 A |
| Diameter of electrode | 2.4 mm |
| Shielding gas      | Ar 4.5|
| Intensity of shielding gas | 15 l min$^{-1}$ |

**3. Examples of numerical simulations**

Modeling the temperature field during surface treatment of 7075 aluminum alloy, the finite element method was solved using ANSYS software. To solve the problems it was necessary to use 4 programs from the ANSYS package [17, 18]:

- Ansys DesignModeler used to perform solid geometry,
- Ansys Meshing used to divide the slab into finite elements,
- Ansys Fluent used to define the model and calculations,
- Ansys CFD-Post for results analysis.

During modelling the temperature field for solids, Ansys Fluent uses the following energy transport equation:

$$\frac{\partial}{\partial t}(\rho h) + \nabla \cdot (\nabla h) = \nabla (k \nabla T) + Q$$  \hspace{1cm} (1)

where: $\rho$ – density, $h$ – enthalpy, $k$ – conductivity, $T$ – temperature, $Q$ – volumetric heat source, $\nabla$ – speed field. As a volumetric heat source in the process of modeling the temperature field during surface treatment, a double ellipsoidal mobile heat source described by Goldak [19] illustrated in figure 4 was used. The Goldak model consists of two semi-ellipsoidal volumes forming a heat flux, for the points $(x, y, z)$ describe the equations for ellipsoids: in front of the source:

$$q_f(x, y, z) = \frac{6\sqrt{3} \pi \rho}{abc \sqrt{\pi}} \exp \left(\frac{-3x^2}{a^2}\right) \exp \left(\frac{-3y^2}{b^2}\right) \exp \left(\frac{-3z^2}{c^2}\right)$$  \hspace{1cm} (2)
and for the back of the source:

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

(3)

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

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

3.1. Modeling of the temperature field during surface treatment of 7075 aluminum alloy sheet with the GTAW (142) method

The block was divided into 495776 cubic elements and 571927 nodes. The mesh was compacted in the bead area (figure 5).

**Figure 5.** Finite element mesh for surface machining of 7075 aluminum alloy sheet by GTAW (142).

Boundary conditions:

- **Dirichlet boundary condition:**
  $$T_s = f(x, y, z, t)$$
  (4)

- **Neumann boundary condition:**
  $$q_s = -k \frac{dT(0, t)}{dx}$$
  (5)

- **Convection boundary condition:**
  $$q_{conv} = h(T_{free} - T_s)$$
  (6)

- **Radiative condition:**
  $$q_{rad} = \varepsilon \sigma (T_{\infty}^4 - T_s^4)$$
  (7)
Thermo-mechanical parameters in relation to temperature are presented in Table 4 and Figures 6–8.

Table 4. Thermal-mechanical parameters in relation to temperature.

| Temperature (°C) | Density (kg m⁻³) | Specific heat (J kg⁻¹°C⁻¹) | Thermal conductivity (W m⁻¹°C⁻¹) |
|------------------|------------------|----------------------------|----------------------------------|
| 26.85            | 2810             | 862                        | 121.62                           |
| 126.85           | 2780             | 913                        | 131.69                           |
| 226.85           | 2760             | 955                        | 140.74                           |
| 326.85           | 2740             | 994                        | 148.75                           |
| 426.85           | 2720             | 1036                       | 155.74                           |
| 526.85           | 2696             | 1084                       | 161.70                           |
| 626.85           | 2670             | 1146                       | 166.63                           |
| 726.85           | 2642             | 1225                       | 170.53                           |
| 826.85           | 2612             | 1324                       | 173.51                           |

Figure 6. Effect of temperature on Al7075 alloy density.

Figure 7. Effect of temperature on Al7075 alloy specific heat.

Figure 8. Effect of temperature on Al7075 alloy thermal conductivity.
Parameters of the surface treatment process for individual 4 passes are in table 5 presented.

|                         | Pass 1 | Pass 2 | Pass 3 | Pass 4 |
|-------------------------|--------|--------|--------|--------|
| **Power arc (W)**       | 1710   | 1710   | 1710   | 1710   |
| **Arc energy (J mm⁻¹)** | 513    | 513    | 513    | 513    |
| **Velocity of welding (m s⁻¹)** | 0.00333 | 0.00667 | 0.00833 | 0.01   |
| **Heat transfer coefficient (W m⁻²K⁻¹)** | 30     | 30     | 30     | 30     |
| **External emissivity** | 0.5    | 0.5    | 0.5    | 0.5    |

3.2. Modeling of the temperature field during surface treatment of 7075 aluminum alloy sheet with the GTAW (142) method at velocity 20 cm min⁻¹.

The temperature distribution at the cross section in time \( t = 15.8 \) s from the start of treatment for the first pass is in figure 9 presented. The graph shows the temperature change when the distance to the heat source changes. We can notice a sharp drop in temperature in the initial phase of the chart. Figure 10 shows a welding thermal cycle for two points, which have been simulated for surface treatment of 7075 aluminum alloy sheets by the GTAW method (142) during first run.

The correctness of the simulation results is confirmed by experimental measurements (figure 11). The calculated full melted zone in which the material has reached a temperature above liquidus is marked in red. Comparison of the theoretical dimensions of the melting zones with the specified experimentally showed differences of less than 5 %.

![Figure 9. Temperature distribution during surface treatment of 7075 aluminum alloy sheet by GTAW (142) at time \( t = 15.8 \) s from the beginning of the process.](image-url)
Figure 10. Thermal cycles for two points during surface treatment of 7075 aluminum alloy sheet by GTAW (142).

Figure 11. The remelting zone during modeling of the temperature field by surface treatment of 7075 aluminum alloy by GTAW (142) in comparison with the experimental study for first pass.

3.3. Modeling of the temperature field during surface treatment of 7075 aluminum alloy sheet with the GTAW (142) method at velocity 40 cm min⁻¹

The temperature distribution at the cross section in time \( t = 7.8 \) s from the start of treatment for the second run is in figure 12 presented and thermal welding cycles are shown in figure 13.

Similarly to the previous study, satisfactory agreement was obtained between numerical and experimental results (figure 14).
Figure 12. Temperature distribution during surface treatment of aluminum alloy sheet 7075 by GTAW (142) at time $t = 7.8$ s from the beginning of the process.

Figure 13. Thermal cycles for two points during surface treatment of aluminum alloy sheet 7075 by GTAW (142).
Figure 14. The remelting zone during modeling of the temperature field by surface treatment of 7075 aluminum alloy by GTAW (142) in comparison with the experimental study for second pass.

3.4. Modeling of the temperature field during surface treatment of 7075 aluminum alloy sheet with the GTAW (142) method at velocity 50 cm min⁻¹

Temperature distribution during third pass in GTAW treatment of aluminum alloy sheet at time $t = 6.4 \text{ s}$ from the beginning of the process is shown in figure 15. The calculated welding thermal cycles for the selected two cross-sectional points are illustrated in figure 16.

The results of the numerical simulations performed give satisfactory results (figure 17). The red remelting zone marked in red on the left is obtained in the simulation for velocity 50 cm min⁻¹. The dimensions of the total remelting zone have been compared with experimental tests and give discrepancies below 5%.

Figure 15. Temperature distribution during surface treatment of aluminum alloy sheet 7075 by GTAW (142) at time $t = 6.4 \text{ s}$ from the beginning of the process.
3.5. Modeling of the temperature field during surface treatment of 7075 aluminum alloy sheet with the GTAW (142) method at velocity $60 \text{ cm min}^{-1}$

Temperature distribution in cross-section of GTAW surface treatment of aluminum alloy sheet 7075 by during fourth pass at time $t = 5.2 \text{ s}$ from the beginning of the process is presented in figure 18. Welding thermal cycles were calculated for two selected points of this section, which are shown in figure 19. As in the previous three numerical and experimental studies give satisfactory consistency of results (figure 20). Comparison of the theoretical dimensions of the melting zones with the specified experimentally showed differences of less than 5%.
Figure 18. Temperature distribution during surface treatment of aluminum alloy sheet 7075 by GTAW (142) at time $t = 5.2$ s from the beginning of the process.

Figure 19. Thermalcycles for two points during surface treatment of aluminum alloy sheet 7075 by GTAW (142).
Figure 20. Remelting zone during modeling of the temperature field by surface treatment of 7075 aluminum alloy by GTAW (142) in comparison with the experimental study for fourth pass.

4. Conclusion
Numerical simulations of the temperature field during surface treatment of 7075 aluminum alloy sheet without additional material at different heat source travel speeds allowed the determination of the remelting zone in the conducted tests. The simulation results have been experimentally verified by comparing the dimensions of remelting zones obtained in the simulation with the metallographic specimen obtained as a result of experimental tests. The correctness of the numerical model confirms the compatibility of the shapes and dimensions of the remelting zones defined theoretically (numerically) and obtained experimentally.

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