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Research Paper

Microstructural analysis in GTA aluminum alloy welding using inverse problems

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HIGHLIGHTS

- A numerical study of heating and cooling rate in a GTA aluminum welding process.
- A linear dependence of the grain size in relation to the positive polarity was observed.
- Correlations between the cooling rate and the grain size of heat affected zone (HAZ).
- A thermal analysis of the HAZ using software based on a numerical heat transfer model.
- The microstructural changes happen while the GTA arch torch was turned on.

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ABSTRACT

Numerical software based on the tridimensional diffusion equation with a moving source, a phase change and heat flux estimation by the non-linear interactive Broydon–Fletcher–Goldfarb–Shanno (BFGS) inverse technique was used to study the heat affected zone (HAZ) in GTA aluminum 6065 T5 alloy welding. GTA welding experiments were performed using thin aluminum plates in four $t+$ experimental conditions. In previous studies, the authors determined that the peak temperature tends to increase as the positive polarity becomes higher. To confirm this behavior, the samples were cut on the welded region and later characterized using an optical microscope (OM) and a scanning electronic microscope (SEM). The heating and cooling rates, determined from an in-house code, were compared with the microstructures and the grain size of the HAZ found in the samples. The results revealed a linear correlation between the grain size on the HAZ and the positive polarity. The study also showed that a significant change in the microstructure occurs during the process while the GTAW torch is still turned on. After the welding, when the GTAW torch was turned off, the cooling rate was the same for all welded zones, which indicates that the microstructural changes had already occurred.

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1. Introduction

Although several new processes to join metals have been developed, the fusion welding process still plays a major role in engineering practice. Hence, a deep understanding of the behavior of microstructural welding is highly important for minimizing potential failures. The heat affected zone (HAZ) is a region where the microstructure is negatively affected during the welding process. The HAZ is fundamentally caused by the characteristic overheating and supercooling of the welding process. The thermal cycle that results in the recrystallization during welding is primarily composed of two steps: heating and cooling [1]. This cycle triggers a microstructural change in the base material (BM), thereby creating the HAZ. Although the heating rate is important to achieve the fusion, the cooling rate is extremely important for the welding quality. During welding, a high cooling rate may generally be associated with the reduction of mechanical properties [2], cracking [3], deleterious phase precipitation [4], or susceptibility to intergranular corrosion [5].

Recently, an increasing interest in the impact of cooling rate on welding properties may be pointed out. For instance, Sivaprasad and Raman [6] analyzed the influence of cooling rate on microstructure and mechanical properties of alloy 718 when it is welded through two distinct welding processes, GTA (gas tungsten arc) and EB (electron beam). Manikandan et al. [7] studied the Laves phase formation in Inconel 718 in the cooling of a welding process. Aissani et al. [8] used a three-dimensional finite element model to analyze the evolution of the microstructure in the weld HAZ in a TIG

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(tungsten arc gas) process. Di et al. [9] used experimental measurements to determine the average cooling rate in local dry underwater welding. The authors' analyses suggest that a fast cooling rate, in this process, may improve the weld properties.

A precise determination of the cooling rate is difficult to achieve. Several authors merely assume that the cooling rate is an intermediate value between the peak temperature and the room temperature divided by the time of cooling [10], while others obtain the value using mathematical models based on the one-dimensional heat diffusion equation, for example, in Bhattacharya et al. [11]. Another option is the use of numerical thermal models for the prediction of the microstructure parameters [12]. However, major simplifications are constantly being made to reduce the complexity of this type of model, e.g. Unfried et al. [13], who assumed a one-dimensional heat flux and a one-dimensional thermal model based on Rosenthal's equations. Another example is the work developed by Manvatkar et al. [14]. To estimate the peak temperature and cooling rate, the authors used an analytical expression proposed by Schmidt et al. [15]. The use of analytical expressions for the estimation is convenient; however, these models do not cover all experimental errors, thereby raising inaccuracies in the solution. The use of commercial software is another alternative to determine the cooling rate [16]. In contrast to the use of an analytical expression, the commercial software acts as a black box, i.e., the user does not have access to its methodology. In fact, due to certain experimental singularities, such as the non-uniformity of the torch arc and the electrical interference on measurements in aluminum welding, a three-dimensional numerical thermal model that covers all boundary conditions is highly complex. In addition, directly measuring the heat flux during the process is expensive. However, the use of inverse problems enables a quick determination of this parameter [17].

Lately, several authors have been using inverse models to estimate the amount of heat flux delivered during a diverse range of welding processes. For example, Gonçalves et al. [17] applied the Golden Section Inverse Technique to estimate the heat input in a TIG welding process. Yang et al. [18] used the conjugate gradient method and the discrepancy principle to minimize the heat flux generation in a rotary friction welding. The aforementioned work demonstrates the versatility of the use of inverse problems in the estimation of the welding heat flux.

A common process extensively used to weld aluminum alloys is GTAW (gas tungsten arc welding). Recently, several authors have been conducting studies on the analysis of the microstructure of this welding process. Kumar et al. [19] presented a mathematical model to predict the grain size in the fusion zone for an AA6061 GTAW process. Zervaki et al. [20] analyzed the HAZ during aluminum welding using an inverse and direct modeling. The authors' model satisfactorily predicted the hardness; this result demonstrated the feasibility of the inverse analysis as a way of control and quantitative prediction of the welding properties.

In previous work, Magalhães et al. [21] developed a C++ code based on the non-linear three-dimensional heat diffusion equation with phase change and moving heat source to study a GTA welding process in AA6065 T5 samples. The inverse method Broydon–Fletcher–Goldfarb–Shanno (BFGS) was used to minimize the heat input. The software was validated by accomplishing lab experiments. This work has a focus on the heat diffusion in the welding of aluminum.

In the present work, the code developed by Magalhães et al. [21] was slightly modified to determine the cooling rate at the FZ, HAZ and BM. The proposed analyses are an inexpensive alternative to precisely determine the instantaneous heating and cooling rate without the requirement of room-controlled temperature, calorimeters, or commercial software. The precise determination of those parameters is decisive to improve the fusion and welding quality. In summary, the study presents an alternative approach to investigate the cooling rate influence of GTA welding on the microstructure of AA6065 T5 samples. Furthermore, the correlations between the heat input on the weld, the time that the electrode remains on the positive polarity, *t*+, and the grain size of the HAZ were also investigated systematically.

2. Materials, experiments and simulations

2.1. Materials and methods

The 6060-T5 250-mm long, 38-mm wide and 6.5-mm thick aluminum plates (Mn 0.15%; Fe 0.20%; Mg 0.45%; Si 0.40%; Cu 0.02%; Zn 0.05%; Ti 0.01%) were welded through a GTA process at LAPROSOLDA (Federal University of Uberlândia – Brazil). The experimental temperatures were obtained on accessible points of the sample. An automated system was used with the weld velocity at 250 mm/min. The time duration that the electrode remains in the positive polarity on the sample, *t*+, was tested in four experimental conditions, 2 ms, 7 ms, 11 ms and 13 ms. On each one, the three experiments were performed to ensure the repeatability of the results. The welding experiment procedure and the experimental apparatus were described in Magalhães et al. [21].

After the welding, the samples were cut with an abrasive saw, and the remaining deformed material was later removed by wet grinding and polishing. The samples were grinded using a Struers DPA motor-driven belt grinder in successive steps using silicon carbide abrasive papers of 400, 600, and 1200 grit. The mechanical polishing was accomplished in two steps: first, a suspension of 600-grit alumina (Al_2O_3) powder in distilled water was used in the Struers DPA motor as a rough polishing. The final polishing was performed using a 0.04-µm suspension of silicon dioxide (SiO_2) in distilled water. A concentrated solution of Poultron's reagent modified (50 mL of Poultron's reagent (30 mL of HCl; 15 mL of HNO_3; 2.5 mL of HF; 2.5 mL of H_2O), 25 mL of HNO_3 and 40 mL of a solution of 3 g of chromic acid per 10 mL of H_2O) was prepared as an etchant in the microscopic examination [22]. The microscopic analysis was performed using an Olympus BM41M-LED optical microscopic and a ZEISS EVOMA15 scanning electron microscope (SEM). The aforementioned preparations and analyses were conducted at the Metallurgy and Materials Laboratory of the Federal University of Itajubá (UNIFEI).

2.2. Simulations

To simulate the problem, the C++ in-house code accounted for a non-uniform mesh with 225.000 volumes. Details of the software's theoretical development, boundary conditions and thermal properties have been reported in Magalhães et al. [21]. The software considered temperature values from six different points, as shown in Fig. 1, for all four experimental conditions. Points P_1 and P_2 are positioned in the fusion zone, points P_3 and P_4 are in the HAZ, and points P_5 and P_6 are in the base material.

As the fusion zone and the HAZ size vary according to the positive polarity, different coordinates of the *P* points were adopted for each adjusted positive polarity condition. The coordinates of the *z* point are presented in Table 1. The *z-axes* orientation is defined as presented in Fig. 1.

The heating rate was defined as the positive numerical derivative of the considered points and may be expressed as:

$$\frac{\partial T(x,y,z,t)}{\partial t} = \frac{T_{P_i}^{a+1} - T_{P_i}^{a}}{\Delta t}, \tag{1}$$

where T is the temperature, x, y and z are the Cartesian coordinates of the respective points P_i, i is the point index, and a is the time step.

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