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Technical Report

Analysis of heat input effect on the mechanical properties of Al-6061-T6 alloy weld joints

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ABSTRACT

Plates of AA6061-T6 with 4.8 mm of thickness were welded with an ER4043 electrode (1.19 mm in diameter) using the typical simple butt joint to investigate the effect on the mechanical properties of aluminum alloy 6061-T6 due to the Gas Metal Arc Welding (GMAW) process. The parameters involved in the welding process were related to the variation of the yield strength and microhardness. A transient thermal analysis was developed to model the problem in a numerical form using Finite Element Method (FEM) and these results were compared with experimental data showing good agreement. It was observed that the amount of energy absorbed by the base material determines the maximum temperatures reached by the aluminum and microstructural changes produced by high metal temperatures, significantly influence the properties of the alloy. For a case with 120 A, 18.0 V and 5.26 mm/s in travel speed, the reduction of yield strength was 45.1% and for Vickers microhardness was 45.2%. For another case with 140 A, 20.5 V and 5.36 mm/s in travel speed, the reductions were 40.9% and 38.4% for yield strength and Vickers microhardness respectively. The transformation of precipitates β'' in β' and β explain these changes.

1. Introduction

The effect of heat generated by the Gas Metal Arc Welding (GMAW) process on AA6061-T6 alloy has been widely studied in the literature. Investigations about the influence of the grain size in the weld heat-affected zone had been considered [1]. In addition, the effect of heat input using the hardness profiles was analyzed [2] and also the heat effect via the evolution of precipitates [3]. GMAW is one of the most used joining techniques and the heat generated by this welding process has been studied for several aluminum alloys (series 6000, 7000 and 8000). The GMAW process had been described by several authors [3–5]; thus different aspects of the process are being studied, including the residual stress [6,7], overthickness, porosity, cracking and the degree of involvement of heat resistance. Most recently, the influence on the microstructure and strength due to interactions between different groups of particles that form at various temperatures was studied [8]. According to [9] the ultimate strength significantly reduces to more than 50% with respect to the base material. An analysis of the mechanical strength for Al-6061-T6 and its microstructure, for different types of welding joints [10] and also a study for the local mechanical properties using micro-traction and instrumented indentation [11] has been developed. Also the influence of welding parameters on fatigue life has been studied by [12].

However, only one reference quantified the reduction on the mechanical properties based on the ultimate strength [9] even when in most design applications the failure criteria is related to the yield strength. Therefore, the purpose of this research is to characterize the mechanical behavior of the welded joint using the yield strength and the microhardness. The approach employed to analyze this problem would be a practical tool to design welding processes and predict the final properties of a mechanical welded component. Several works have been developed in the correlation among process variables, microstructure and mechanical properties [13–15]. This article focuses on the effect of heat input on mechanical properties such as yield strength and microhardness and its relationship with GMAW process parameters such as travel speed, current intensity and voltage as shown in Fig. 1. A numerical model for the thermal analysis was generated and implemented computationally and the results were validated with experimental data. Transmission Electron Microscopy (TEM) and Differential Scanning Calorimetry (DSC) were used to characterize the evolution of hardening precipitates β'', β' and β and the intermetallic compound Mg_2Si.

2. Proposed thermal model

To model this thermal process, the heat absorbed by welded sheets has to be calculated. In this analysis radiation and convection losses are considered. Other losses are not taken into account because their magnitudes are not significant. Eq. (1) describes the

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Nomenclature

C_p	fluid heat capacity (W s/kg °C)
g	acceleration due to earth's gravity (m/s^2)
$\mathrm{Gr_L}$	Grashof number
h_m	mean convective heat transfer coefficient (W/m^2 °C)
HV	Vickers hardness
I	current (A)
k	thermal conductivity (W/m^2 °C)
L	characteristic length (avg. length) (m)
Nu_m	mean Nusselt number
Pr	Prandtl number
Q	heat input (W/m^2)
σ	Stefan–Boltzmann constant (W/(m^2 K^4))
S_u	ultimate tensile strength (MPa)
S_y	yield tensile strength (MPa)
T_∞	bulk temperature (°C)
T_s	surface temperature (°C)
v	voltage (V)
ρ	density (kg/m^3)
υ	kinematic viscosity (m^2/s)
ε	emissivity

radiation losses that mainly occur in the weld area (higher temperature) [16]. And this equation assumes no interaction between adjacent surfaces and the hot surface.

$$q_{rad} = \varepsilon\sigma(T_s^4 - T_\infty^4) \tag{1}$$

Applying Eq. (1) for the aluminum: In the hottest area, the value for q_{rad} is 1640 W/m^2; for an average temperature zone of 150 °C then q_{rad} is 53 W/m^2. Table 1 lists the thermal properties for the AA6061-T6 required in the analysis [17].

The following expressions from [18,19] correlates Nusselt, Grashof and Prandtl numbers with mean convective heat transfer coefficient. For a horizontal plate:

$$\mathrm{Nu}_m = c \cdot (\mathrm{Gr}_L \mathrm{Pr})^n \tag{2}$$

$$\mathrm{Nu}_m = \frac{h_m L}{k} \tag{3}$$

$$\mathrm{Gr_L} = \frac{g\beta(T_s - T_\infty)L^3}{\upsilon^2} \tag{4}$$

where β is the volumetric thermal expansion coefficient (approximately $1/T$, where T is the absolute temperature for ideal fluids).

The values of c and n coefficients depend on the regime and the location of the surface; Table 2 shows them. Table 3 presents the properties of the atmospheric air at different temperatures. Table 4 summarizes the results for different temperatures applying Eqs. (2)–(4). Considering that approximately 80% of the plate remains significantly below the maximum temperature, weighted values

Table 1
AA6061-T6 properties.

Property	Value
$\varepsilon_{\text{polished aluminum}}$	$\varepsilon_{\mathrm{Al}} = 0.04$
Density (ρ)	ρ = 2.7 gr/cm^3
Coefficient of linear thermal expansion (α)	23.6 μm/m K
Fluid heat capacity at 20 °C (C_p)	896 J/kg
Liquidus temperature (T_{liq})	652 °C
Solidus temperature (T_{sol})	582 °C
Thermal conductivity (k)	k = 167 W/m K

Table 2
Values of c and n coefficients for different regimes in free convection. Obtained from [18].

Type of flow	Plate orientation	$\mathrm{Gr_L} \cdot \mathrm{Pr}$ range	c	n
Turbulent	Face up	$[2 \times 10^7 – 3 \times 10^{10}]$	0.14	1/3
Turbulent	Face up	$[10^5 – 2 \times 10^7]$	0.54	¼
Laminar	Face down	$[3 \times 10^5 – 3 \times 10^{10}]$	0.27	¼

Table 3
Properties of the atmospheric air at 30 and 340 °C. Obtained from [18].

	T = 30 °C	T = 340 °C
C_p (W s/kg °C)	1.06	1.025
k (W/m °C)	0.0273	0.0366
ρ (kg/m^3)	1.371	0.8108
υ (m^2/s)	0.1664×104	0.3018×10^4
Pr	0.703	0.686

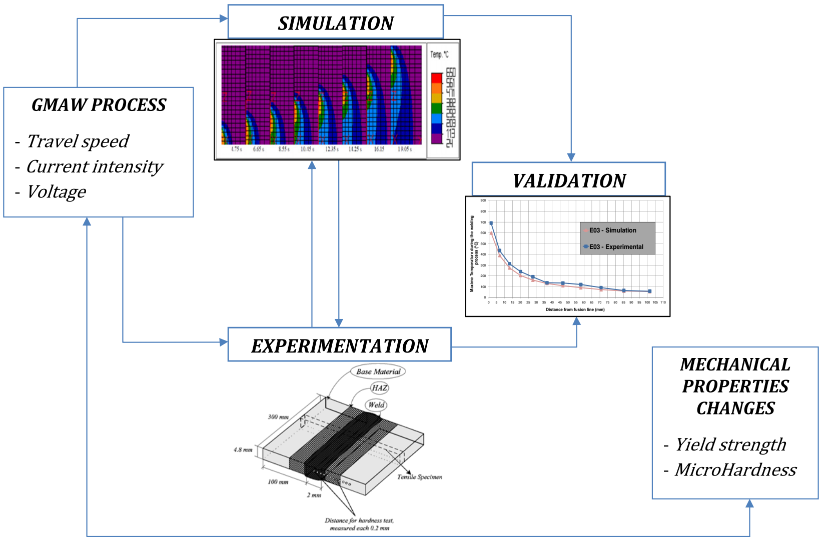

Fig. 1. Flow diagram of the research process.