An alternative to increase the mechanical strength of 6061-T6 GMA weldments

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Fusion welding of heat treatable aluminum alloys leads to a significant loss of strength in the heat affected zone (HAZ) due to overaging. This work was aimed to improve the mechanical properties of Al-6061 welds. Plates of 6 mm in thickness were solutionised at 530°C for 1 h followed by water quenching and aging at 160°C for times between 13 to 19 hours. Welding was performed with the gas metal arc welding process (GMAW). Transverse microhardness indentations and mechanical testing were performed to characterize the overaged zone and mechanical strength of the as-welded joints. It was found that samples partially aged for 16 h exhibited an increase of 30% in hardness values in the overaged zone and accordingly its mechanical strength also increased with respect to the Al-6061-T6 (21 h aging time) as welded plates. Although failure of the welds with the partially aged plates occurred in the HAZ, the larger strength of the 16 hours aged samples suggests that the heat input of the welding process reactivated the precipitation sequence in the base material and the degree of overaging was reduced.

Keywords: Overaging; GMA welding; Al-6061 aluminum alloy, partial heat treatment.

La soldadura de aleaciones de aluminio tratables térmicamente crea una zona con bajas propiedades mecánicas en la zona afectada por el calor debido al sobre envejecimiento del material base. El presente trabajo tiene como objetivo mejorar las propiedades mecánicas de soldaduras de Al-6061. Se solubilizaron placas de 6 mm de espesor a una temperatura de 530°C por una hora y posteriormente se templaron en agua, después fueron envejecidas a 160°C a diferentes tiempos entre 13 y 19 horas. Las uniones fueron realizadas por medio del proceso de soldadura de arco metalico protegido por gas (GMAW). Fueron caracterizadas secciones transversales mediante barridos de microdureza y resistencia a la tensión para caracterizar la zona sobre envejecida y la resistencia mecánica de las soldaduras. Se encontró que las muestras envejecidas parcialmente a 16 horas muestran un incremento del 30% en los valores de microdureza en la zona sobre envejecida, y por lo tanto su resistencia mecánica también incrementó respecto a las placas envejecidas en la condición de soldado (tiempo de envejecido 21 h). A pesar de que la falla ocurrió en la zona afectada por el calor en las soldaduras con las placas parcialmente envejecidas, la mayor resistencia de las placas envejecidas por 16 horas sugiere que la secuencia de precipitación se reactivó en las placas y que se redujo el grado de sobre envejecimiento.

Descriptores: Sobre envejecimiento; soldadura GMAW; Al-6061; tratamiento térmico parcial.

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1. Introduction

The 6000 series aluminum alloys are heat treatable and widely used in structural and functional applications due to their specific mechanical properties, corrosion resistance and formability from simple to complex profiles by extrusion [1]. Fusion welding of these alloys is often required but, unfortunately, weldability problems exist [2]. A great concern is the susceptibility of these alloys to weld cracking which is caused by the relatively high thermal expansion of Al-alloys, their large change in volume upon cooling as well as their wide solidification temperature range [3,4]. This phenomenon dramatically decreases the mechanical properties of the joint [5]. The same effect is observed as a result of the creation of a soft zone in the heat affected zone (HAZ) caused by overaging during the thermal cycle imposed on the joint during welding [2]. The overaging phenomenon, which occurs in the heat affected zone (HAZ), is a solid phase transformation in which coarsening and a change in crystalline structure of the Mg2Si precipitates take place during welding [6,7]. The mechanical properties of the joint for the later case can be restored by postweld heat treating (solutioning, quenching and aging). Rapid quenching, however, can lead to distortion of the welded joint and, inconveniently, in many cases it might not be accessible for heat treating and it has to go on service in the as-welded condition [4]. This study proposes an alternative to confront this problem on an Al-6061-T6 aluminum alloy by making interrupted aging heat treatments prior welding of the 6061 plates. The objective is to interrupt the kinetics of precipitation during aging to subsequently reactivate the process with the welding thermal cycle so that the overaging effect may be avoided or at least minimized.

2. Experimental procedure

Plates of commercial Al-6061-T6 aluminum alloy (0.986wt.%Mg and 0.561wt.%Si) with a thickness of 6 mm were used in this study and a filler wire ER4043 (5.5wt.%Si), 1.2 mm in diameter, was employed to deposit the weld beads. Prior welding, the plates were solutionised at 530°C for 1 h followed by water quenching and aged at 160°C for times between 13 to 19 hours [8]. Plates of base metal, with different aged conditions, were machined to obtain the joint geome-
try shown in Fig. 1. Weld beads with a length of 170 mm were deposited using a semi-automatic GMA welding machine using direct current-reverse polarity, Ar shielding gas (22 L/min), 23 V, 190 A, the filler wire was fed at 180 mm/s, the torch traveled at 3.6 mm/s and the stick out was of 12 mm. For visual examination cross sections of the welded joints were cut and prepared using standard metallographic procedures [9]. To reveal the base metal, HAZ and weld metal, polished samples were etched with a solution of 75 HCl, 25 HNO₃, 5 HF and 25 H₂O (ml). Microhardness measurements were performed, applying a load of 10 g for 10 s with a Vickers indent along of the transverse sections to quantify the extent of overaging and the width of the damaged zone. Tensile specimens were machined according to the ASTM B 557M-94 standard [10] and tested at room temperature, with an universal testing machine at a cross head speed of 0.016 mm/s⁻¹. At least three tensile specimens were tested for each condition and the average value is reported. In order to correlate the location of the soft zone with the weld thermal cycles and phase transformations, K type thermocouples were placed at the failure zone to register the temperatures reached in that region during welding. Fractures were observed and analyzed by SEM in the secondary electrons mode.

3. Results and discussion

Figure 2 shows typical macrostructural features of the welds. On the top view, an excellent surface finish is appreciated without splashes and any kind of discontinuities. That is the result of an adequate spray transfer mode. Regarding the cross section, a fully penetrated weld bead is observed with no undercut and without lack of lateral fusion.

Figure 3 shows the typical microstructure obtained for the welds, which is characterized by epitaxial growth with columnar-dendritic grains competitively growing toward the heat source [11]. Microstructural examination of the weld metal revealed minimum microporosity, continuity between weld and base metal along the fusion line and no cracking. Thus with the welding parameters used and the care taken before and during welding, sound welds were obtained.

Table I lists the mechanical properties of the Al-6061-T6 alloy, welds with the plates in the T6 condition and partially aged for times between 13 to 19 hours. The tensile strength of the Al-6061-T6 alloy is above the nominal strength (310 MPa) for this alloy [12]. A reduction of approximately 50% is observed for the plates welded in the

<table>
<thead>
<tr>
<th>ID</th>
<th>Yield strength (MPa)</th>
<th>Ultimate strength (MPa)</th>
</tr>
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<tbody>
<tr>
<td>Base metal</td>
<td>290.5</td>
<td>330.3</td>
</tr>
<tr>
<td>6061-T6</td>
<td>143</td>
<td>160.3</td>
</tr>
<tr>
<td>13 h aged.</td>
<td>142.5</td>
<td>159.7</td>
</tr>
<tr>
<td>15 h aged.</td>
<td>121</td>
<td>164</td>
</tr>
<tr>
<td>15.5 h aged.</td>
<td>172.5</td>
<td>193.5</td>
</tr>
<tr>
<td>16 h aged.</td>
<td>199</td>
<td>223.5</td>
</tr>
<tr>
<td>16.5 h aged.</td>
<td>136</td>
<td>152.5</td>
</tr>
<tr>
<td>17 h aged.</td>
<td>144.5</td>
<td>162.5</td>
</tr>
<tr>
<td>18 h aged.</td>
<td>150.5</td>
<td>169.3</td>
</tr>
<tr>
<td>19 h aged.</td>
<td>127.5</td>
<td>143.3</td>
</tr>
</tbody>
</table>
AN ALTERNATIVE TO INCREASE THE MECHANICAL STRENGTH OF 6061-T6 GMA WELDMENTS

FIGURE 4. Mechanical strength of the welded joints as a function of aging time.

T6 condition and approximately the same loss of strength occurs in the samples partially aged for 13 and 15 hours. An increase in strength is shown by the plates partially age for 15.5 hours and the highest value in ultimate strength (223.5 MPa) was exhibited for the samples partially aged for 16 hours. This corresponds to a decrease of only 30% with respect to the strength of the base metal and an increase in the joint efficiency of 25% regarding the Al-6061-T6 as welded joint. For longer aging times, the measured mechanical strength suggests that the heat input also reacti-

FIGURE 5. Comparison of the microhardness profiles between the Al-6061-T6 weld and the weld with the plates partially aged for 16 hours.

FIGURE 7. Welding thermal cycles.

Figures 5, 6, 7, and 8 show the results of the mechanical tests and thermal cycles for the Al-6061-T6 weld. Figure 5 compares the microhardness profiles between the Al-6061-T6 weld and the weld with the plates partially aged for 16 hours. Figure 6 shows the location of the K type thermocouples on the welding joint. Figure 7 shows the welding thermal cycles. Figure 8 shows the time-temperature-transformation diagram for the $\beta'$ phase.

In order to clearly observe the behavior of the tensile tests, the ultimate strength was plotted against the aging time as shown in Fig. 4. These results suggest that for aging times of 15.5 and 16 hours, the kinetics of precipitation is reactivated by the heat input of the welding thermal cycle and although peak properties were no achieved, the degree of overaging was reduced. For longer aging times, the measured mechanical strength suggests that the heat input also reacti-
Figure 9. a) Fracture of T6 condition and b) after 16 hours partial aged and then welded.

vated the precipitation sequence but significant overaging was not prevented.

Microhardness profiles correlated well with the tensile results and the weld with the plates partially aged for 16 hours exhibited the most important differences with regard to the plates welded in the T6 condition. Figure 5 compares the behavior of the microhardness profiles of these welds. It is evident in the Al-6061-T6 weld the existence of a soft zone in which Vickers microhardness decreased to values around 60, the location of this zone matches well with the failure zone (HAZ) observed in the tensile specimens.

Once that the overaged zone was located, an experiment was set up to register the thermal cycles developed in that region during welding. The schematic in Fig. 6 and the holes observed in the top view of Fig. 2a show the location of the thermocouples. The data logged during this experiment are plotted in Fig. 7. The important aspect from these profiles is the peak temperatures reached in each thermocouple. Peak temperatures are between 308 to 214°C. Thermocouple 3 was strategically located at the so-called coarsening-transformation zone (CTZ), where coarsening of $\beta'$ phase and its transformation into $\beta''$ phase take place giving rise to the softening of this zone [2]. The thermal cycle recorded by this thermocouple was superimposed to the time-temperature-transformation (TTT) diagram for the $\beta''$ as shown in Fig. 8. It can be seen that the thermal cycle in this zone crosses the TTT curve during approximately 170 seconds which is enough time for the transformation of the coherent $\beta''$ precipitates into the non-coherent $\beta'$ precipitates.

With regard fracture of the tensile samples, Fig. 9 shows typical fracture images for the T6 condition and for the sample aged for 16 h. Where as the first image shows the typical features of a ductile failure (abundant presence of large and deep equiaxed dimples nucleating on second phases, as pointed by the arrows), the second exhibits similar features but evidencing less deformation as a result of the larger strength for this sample. The precipitates observed at the bottom of the dimples in both samples correspond to Mg$_2$Si intermetallics as revealed by energy dispersive X-ray analysis. This feature means that overaging took place in both cases but its extent was different and that was reflected in the tensile results.

4. Conclusions

The results presented here indicate that partially aging of Al-6061 plates is a viable alternative to reduce the degree of overaging and increase the mechanical performance of 6061 plates welded with the GMAW process. Partial heat treatments of artificial aging increased the tensile strength to 223.5 MPa. According to the AWS D1.2 standard, a tensile strength of 160 MPa is acceptable for a 6061-T6 welded joint. The plates artificially aged for 16 hours exhibited the highest tensile strength of 223 MPa and an increase in Vickers hardness in the soft zone. Besides, temperatures measured in the failure zone reveal that under the welding conditions employed, transformation of precipitates occurs. These findings suggest that the heat input of the welding process reactivated the precipitation sequence in the plates and the degree of overaging was reduced possibly due to a partial transformation of $\beta''$ precipitates into $\beta'$ precipitates. Further characterization of the soft zone by transmission electron microscopy is necessary to confirm this phenomenon and assess the extent of overaging.

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