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Effect of heat treatment on the properties of laser-beam welded rheo-cast F357 aluminum

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ABSTRACT

Semi-solid metal rheo-cast F357 aluminum plates were joined by autogenous Nd:YAG laser welding and were welded in either the as-cast (F) condition, T4 temper or T6 temper condition. The weldability of this age-hardenable Al–7%Si–0.6%Mg casting alloy was characterized by assessment of the microstructure in the fusion and heat-affected zones and by measurement of the weld-plate tensile and hardness properties. The low heat input provided by the laser welding process resulted in high cooling rates (450–600 K/s) within the fusion and adjacent heat affected zones. This thermal cycle closely resembles quenching practice for standard solution treatments (500–700 K/s) and as a result the T4 condition was maintained during the welding process. Tensile properties equivalent to the parent metal T6 condition were obtained after exposing welded T4 plates to conventional artificial ageing treatment.

1. Introduction

The Al–Si–Mg casting alloys and particularly alloy A357, which is the equivalent of F357 with added beryllium, are often processed by semi-solid metal (SSM) technology. Rheo-casting is one of two process versions of SSM technology and involves the direct production of a globular metal slurry by cooling/stirring from liquid to the semi-solid state. The globular slurry is injected directly into the die of a high pressure die caster (HPDC), as described by Ivanchev et al. (2008). The SSM casting process offers distinct advantages over conventional near-net shape casting technologies in that it promotes reduced porosity, decreases solidification shrinkage and eliminates dendritic growth during freezing as stated by Kang et al. (2008). The elimination of dendritic growth promotes the formation of near-spherical primary particles in the melt which in turn gives rise to a more or less equiaxed grain structure in the casting. This microstructure, coupled to lower gas and shrinkage porosity obtained with SSM technology, can improve the mechanical properties of castings. Consequently, Kapranos (2008) is of the opinion that the application of the SSM casting process has the potential to open up new opportunities for net-shape forming of high performance products. The versatility of this process can be further extended by ensuring that components are able to be welded to allow more complex product geometries.

The mechanical properties of age-hardenable Al–Si–Mg alloys depend on the rate at which the alloy is cooled after the solution heat treatment, because the precipitation hardening effect is proportional to the level of super-saturation after solution treatment and quenching. Quenching is thus a crucial step in the suppression of the precipitation, the retention of the super-saturated solid solution, the control of distortion and the minimization of residual stress in aluminum alloys. It is also reported by Zhang and Zheng (1996) that the average quench rate within the temperature range of 200–450 °C is the most critical in influencing the strength. Joining by fusion welding can alter the prior solution treatment or age-hardened state and in general a post-weld solution and quenching heat treatment is done to equalize the weld and parent metal strength, as was shown by Akhter et al. (2006). However, it is undesirable to perform solution treatment at high temperatures after welding. The present work therefore investigates the potential for combining the microstructural advantages obtained through SSM casting with the application of laser welding to produce desirable mechanical properties in the T6 condition of the final component without a post-weld solid solution heat treatment. The compatibility between cooling rate during laser welding (which is a critical factor in determining the level of weldability) and the quench sensitivity of the Al–7%Si–0.6%Mg alloy is also determined.

2. Experimental

Laser welding was performed using an aluminum welding head coupled to an articulated-arm robot with a fiber-coupled 4.4 kW

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CW diode pumped Nd:YAG laser which delivers a minimum single focal spot size of 0.4 mm. The beam was adjusted by means of the variable double-focus forming module of the welding head to deliver a longitudinal twin spot configuration with 0.38 mm spot separation distance and 45/55% power intensity distribution between the leading and trailing spots. The long axis of the dual focal spot was orientated in the welding direction and laser power of 3.8 kW and a welding speed of 4 m/min were applied. Welds were performed in the 1G position (square butt preparation) with the incident laser beam perpendicular to the aluminum surface and the focal plane at the top surface. Helium at a flow rate of 10 l/min was applied as shielding gas via a leading off-axis nozzle based on a concept used by Haboudou et al. (2003). Argon at a flow rate of 5 l/min was applied as the root purging gas.

Cast plates measuring 100 mm × 90 mm × 6 mm were produced from the F357 aluminum alloy which is nominally composed of Al–7%Si–0.6%Mg alloy without beryllium. Prior to casting via a high pressure die-casting press the metal was conditioned to the semi-solid metal (SSM) state using the CSIR's rheo-technology developed by Ivanchev et al. (2004).

The cast plates were laser butt welded in different heat treated conditions, namely as-cast (F), T4 and T6 temper. The process sequence in each case is presented in Table 1. The T4+ condition is special in that it refers to plates that were heat treated to the T4 condition before welding and only artificially aged after welding.

Since this study focuses on the interaction between quench sensitivity and weld cooling rate, the plates were skimmed down (both sides) from the as-cast thickness to 3.5 mm to eliminate possible surface defects, irregularities or damage obtained during heat treatment. Machining of edges was performed to optimize weld fit-up and all surfaces were cleaned in solvent and wire-brushed prior to autogenous butt welding in order to remove oxide and contaminants from the surfaces.

Parent metal and weld joint sub-size tensile specimens were machined from the F357 samples for all the respective heat treatment conditions. The tensile specimens conformed to ASTM B557M and where relevant the weld joint was centred along the tensile specimen gauge length. All excess weld metal and excessive penetration were machined off to equal the thickness of the parent material and to eliminate any strengthening effect from weld build-up.

After welding, all plates were radiographically tested in order to evaluate possible internal weld defects. Transverse, through-thickness sections of the parent material and weld joints of the F357 samples were prepared by conventional metallographic procedures and etched with Keller's reagent. The microstructures were examined in bright-field mode using low and high magnification light microscopes. Vickers micro-hardness ($HV_{0.3}$) traverses were performed across the transverse weld joint samples (parent metal to parent metal) at mid-thickness in all heat treatment conditions.

In order to assess the quenching effect during laser welding of F357 aluminum, the cooling rate of the metal during quenching after solution treatment and after laser welding was determined from the average of 3 and 9 trials respectively. For the solution treatment practice, a K-type wire thermocouple was press-fit into a blind hole which was drilled down to mid-thickness in the centre of a cast plate sample. The sample was soaked at 540 °C and quenched in water to room temperature. To measure the cooling rate after the laser welding pass, a C-type thermocouple was pressed into one of the butt faces and bent through 90° to secure the position within the weld. In this way butt welds (0.5 mm off-set) could be successfully performed with the thermocouple in the fusion zone. In both cases the thermocouples were coupled to an oscilloscope for fast data acquisition (2500 readings/s) and the emf readings from the thermocouples were converted to degrees Celsius.

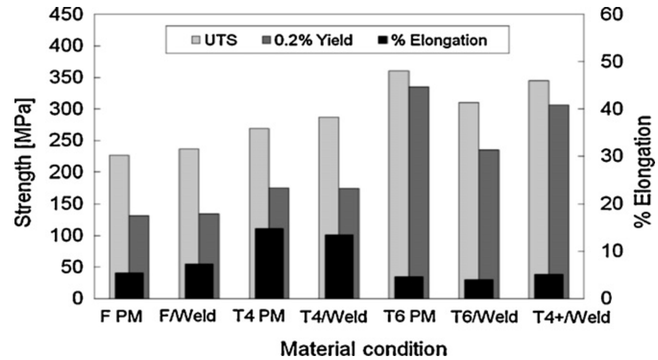

Fig. 1. Tensile properties for the parent metal and as-welded joints of the F357 material in all pre-weld heat treated conditions, except for the post-weld artificial ageing of T4+ condition.

3. Results

The tensile property specification requirements according to MatWeb (2011) for Permanent Mold Cast A357.0-T61 aluminum are given in Table 2, together with average tensile properties that have been reported in the open literature for A357-T6 rheo-diecast components (Fan et al., 2005) and F357-T6 permanent mold components (Yang et al., 2005). These values are reported here in order to compare with the actual tensile properties that have been measured in the present study. The 0.2% yield strength, ultimate tensile strength (UTS) and % elongation to fracture values for tensile tests performed on specimens in the as-cast (F), T4, T6 and T4+ conditions are presented in Fig. 1. Results are reported in each case for the specimens prepared from the parent metal (PM) and specimens prepared from the weld zone.

The welded T6 condition tensile samples fractured in the WM or HAZ (Fig. 2(b) and (c)) whereas 86% of the other weld test conditions (F, T4 and T4+) failed in the parent metal during tensile testing (Fig. 2(a)).

The hardness of the F357 parent material in all the heat treated conditions was measured to be 75 $HV_{0.3}$ average in the as-cast condition, 95 $HV_{0.3}$ in the T4 condition, 125 $HV_{0.3}$ in the T6 condition and 128 $HV_{0.3}$ in the T4+ condition. Therefore, the heat treated parent material shows enhanced hardness from the F to T4 to T6 condition. The average weld metal hardness is just below 100 $HV_{0.3}$ and is the same for all as-welded F357 samples due to the same weld parameters being used and no post-weld heat treatment applied. The weld metal (WM) hardness is higher than the parent metal (PM) hardness in the F condition, slightly higher than the T4 parent metal, and lower than the T6 parent metal hardness as shown in the hardness profiles that were measured on metallographic sections perpendicular to the welding pass (Fig. 3). In the case of the T4+ condition, the weld metal hardness has increased substantially and is almost as high as the hardness obtained in the parent metal where the latter has effectively experienced the complete T6 heat treatment.

The weld joint bead profile and geometry were similar for most of the welds and were characterized by small protruding weld roots (excessive penetration – Fig. 4). The latter is ascribed to the sagging of low viscosity weld metal when welding is performed in the 1G position. The only internal defect observed in the welds was a low degree of porosity. All welds were analyzed according to the ISO 13919-2:2001 specification and met all the applicable Level B (stringent) requirements. The specification allows the summation of projected areas of pores or cavities to be ≤3% whereas in this study values of ≤1% were recorded. Furthermore, the radiographic analysis revealed full compliance with the requirements for localized (clustered) and linear porosity.