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Investigation of Fusion Weldments of Semi-Solid Aluminium A356 Alloy: Pool Geometry and Microstructure

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Abstract. A fusion welding technique to join a semi-solid processed A356 cast plate is explored using Gas Tungsten Arc Welding (GTAW). Semi-solid metal (SSM) billets of non-dendritic microstructure produced by rheocasting in a mould placed inside a linear electromagnetic stirrer were used for this study. GTAW experiments were conducted to simulate different thermal gradients near the fusion zone. The geometries of the weld pool as well as the temperature gradient in the fusion boundary were measured to understand the microstructure evolution. Simulation of the welding process was performed to aid in the analysis. Quantitative metallography provided the shape factor as a measure of globularity of the primary a-Al phase. Based on the studies, a model has been proposed to explain the observation of globular microstructure in the fusion zone of the welds. Conclusions show a positive correlation of thermal gradient with globular microstructure formation in this class of alloys.

Introduction

Cast aluminium alloys are extensively used in aerospace and automotive industries due their higher specific strength. Semi-solid processing involves [1,2] shearing of the metal in the mushy state during solidification to alter the dendrite morphology of the solid into a spherical/globular microstructure.

GTAW is usually the fusion welding technique selected for aluminium alloys. The partially melted zone (PMZ) is the region adjacent to the fusion zone (FZ), where liquation occurs due to heating above eutectic temperature [3]. It is known that the temperature gradients determine the width of the PMZ and thus play a vital role in the nucleation mechanism and microstructural evolution in the fusion zone. By modifying the convective heat transfer conditions, it is possible to change the width of the PMZ in Gas Tungsten Arc (GTA) weldments [4]. GTA weldments in aluminium alloys generally exhibit dendritic microstructures. This study aims to demonstrate that by increasing the width of the PMZ, one can obtain a near globular microstructure in weldments of SSM alloys.

Experimental Details

Semi-solid processed A356 billets were produced from a Linear Electromagnetic Stirring (LEMS) setup of the rheocasting type [5]. Cast plates of thickness 8 mm were used in this investigation. Bead-on-plate tungsten inert gas (TIG) welding was performed on the aluminium plates using a current of 150 A and voltage 16.5 V and argon was used as the shielding gas. TIG welding of the plates was performed under two conditions, 1) SSM with copper backing plate and 2) SSM with copper backing plate and water cooling. Type “K” thermocouples were inserted into drilled holes in the plates and thermal cycles were recorded using a computer based data acquisition system. The experimental arrangement is shown in Fig. 1.

Metallographic samples of transverse cross-section were taken at the centre of the welds. The microstructures of the FZ and PMZ were observed using optical microscopy. The morphology of grains, was analysed by measuring a shape factor the $(4\pi A)/P^2$. Image analysis was performed to determine the cross sectional area (*A*) and perimeter (*P*) of the primary α particles. For a spherical/globular microstructure the value tends to 1 and for a dendrite the value tends to zero [2,6].

Fig. 1. Typical bead-on plate weld showing copper backing and water cooling arrangements.

Simulation Procedure

Since the weld geometry and thermal cycles are influenced by the heat transfer in the whole weldment, 3-D finite element modelling has been used to determine the thermal gradients near the fusion boundary. The heat transfer calculation was focused on the prediction of thermal distributions in the whole weldment and the size and shape of the FZ and PMZ. The objectives of the model were to generate a 3-D finite element model (FEM) using SYSWELD®, to understand the thermal history along the fusion boundary and to determine the size of the weld pool. The weld zone and PMZ are modelled with finer mesh elements for better aspect ratio. Away from the weld line the mesh becomes coarser and penta elements are used for transition between finer and coarser mesh. The typical grid system used in this simulation contains 69889 nodes and 75554 3-D elements to represent the plate materials, 11384 surface elements to represent convective heat loss between the plate and the atmosphere. There are about 64080 1-D elements to model the weld path.

Temperature dependent properties [7] such as thermal conductivity and specific heat used in the simulation are not listed here for brevity. Density was assumed to be 2369 kg/m^3 and is independent of temperature. The liquidus and solidus were taken to be 650 °C and 585 °C, respectively.

Heat Source Fitting (HSF) tool is the facility available within the SYSWELD® software, which enables the user to calibrate the heat source parameters to perform transient thermal analysis of welding. Since this analysis is concerned with TIG welding, a pre-defined double ellipsoidal heat source model defined by Goldak and co-workers was selected [8,9]. The calibration of heat source parameters was achieved by a combination of two methods. Firstly, a temperature contour plot showing different regions of the weld zone was taken and compared with the metallographic cross-sections of the weld profile taken using low magnification stereo microscopy. Secondly, the time-temperature plot of HSF tool weas compared to the thermocouple readings taken during experimentation. The heat source parameters are adjusted in an iterative manner to achieve best fit.

Results and Discussions

The typical transverse section of a weld profile obtained for the TIG welded A356 is shown in Fig. 2. The microstructure of the base metal (Fig. 3) consists of non-dendritic primary a grains surrounded by a near-eutectic secondary phase composed of aluminium and silicon grains.

In the PMZ where the temperature is within the freezing range of the alloy, the inter-globular eutectic is expected to be molten and the globular α-Al grains of the base metal are expected to get detached. These grains get advected towards the solidifying front due to weld pool convection and drag on the grains as schematically shown in Fig. 4. These advected grains could then act as heterogeneous nucleation sites for the solidification of the weldment in a globular fashion. A lower thermal gradient near the edge of the meltpool and a larger PMZ width should imply a larger number of nucleation sites and thus lead to finer weldment microstructure that is also globular. The experimental measurements detailed ahead corroborate this model.

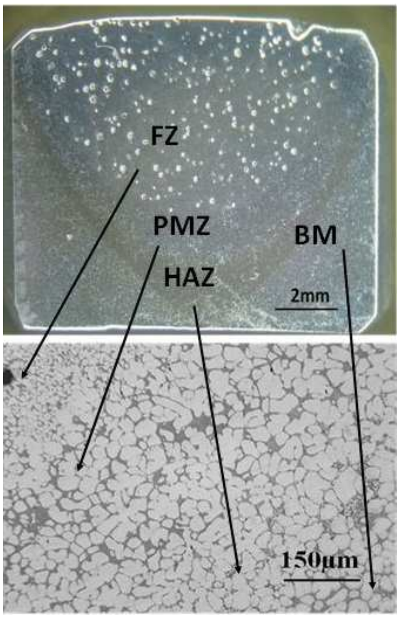


Fig. 2. Optical micrograph of the weld zone in a TIG weld of semi-solid A356.

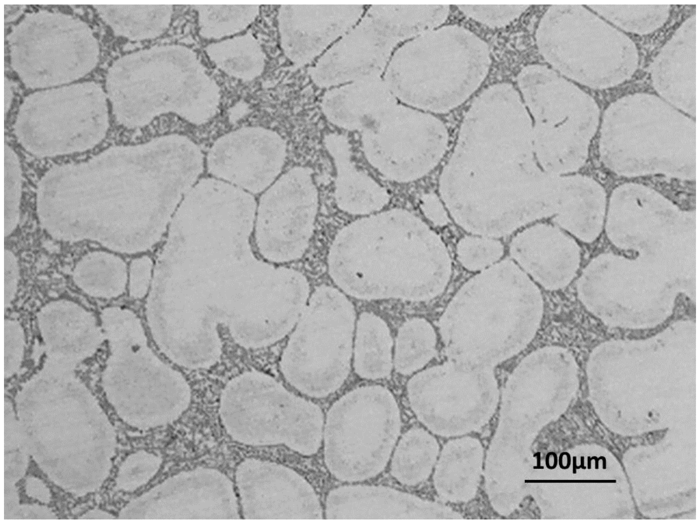


Fig. 3. Microstructure of the base metal.

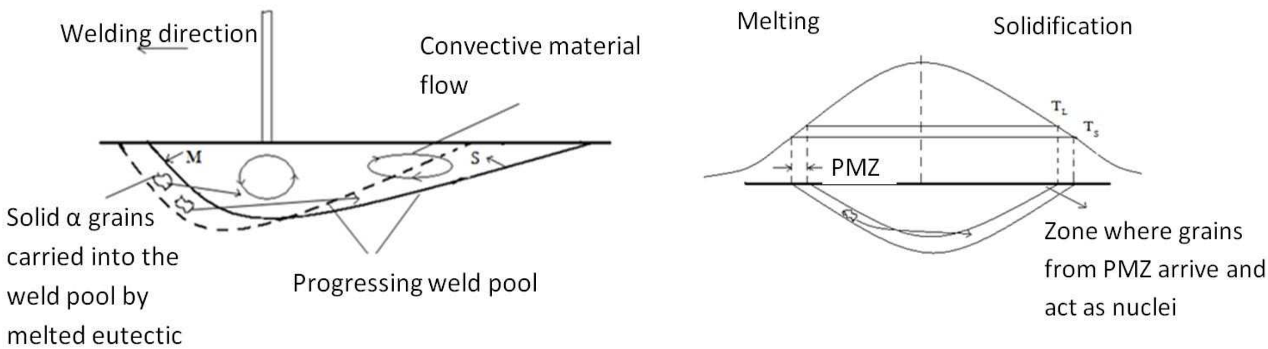
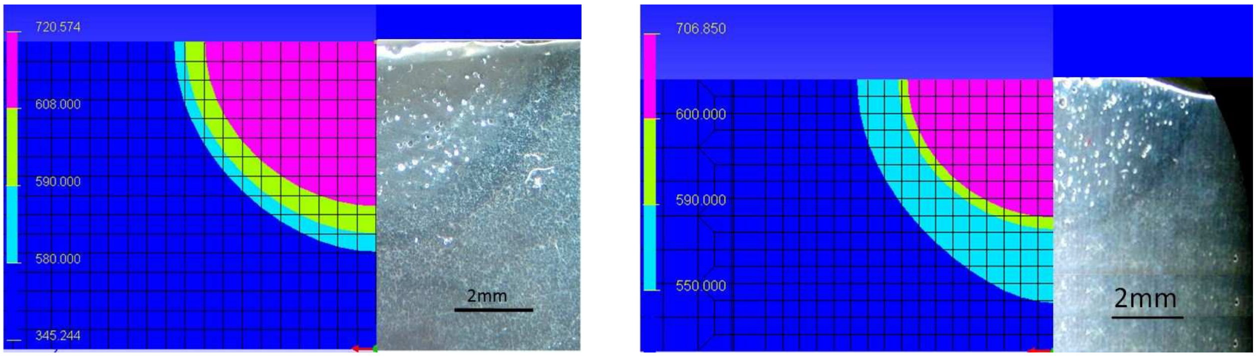


Fig. 4. Schematic showing a possible mechanism occurring in fusion zone.

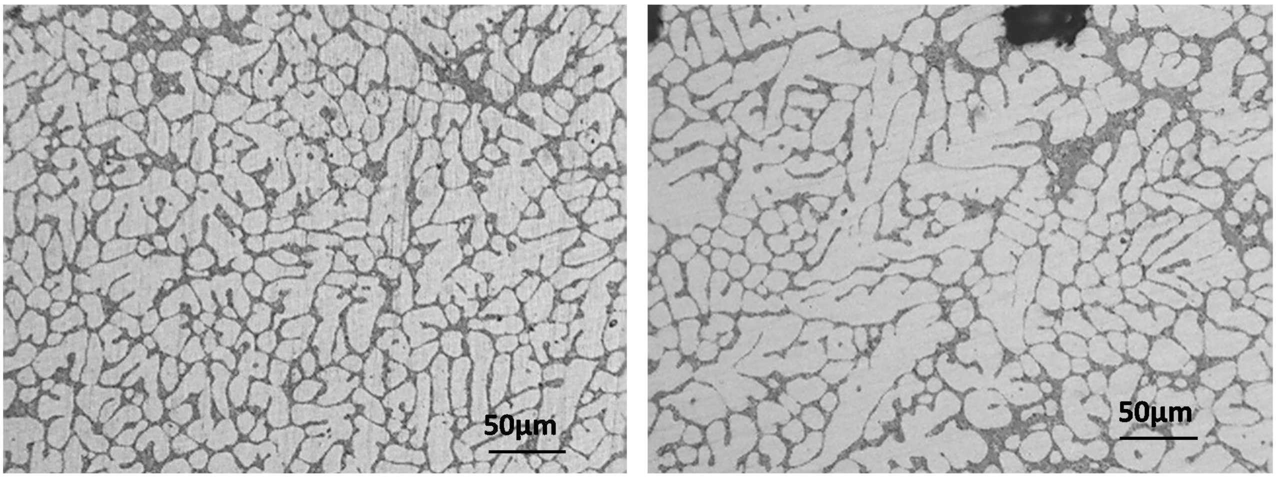
Fig. 5a&b shows the comparison between measured and calculated weld pool geometries and thermal profiles in the FZ and PMZ for the TIG welds with copper backing plate and both copper backing and water cooling arrangements respectively. The convective heat loss is predicted with a heat transfer coefficient value (h). For copper backing plate h = 250 Wm^{-2} K^{-1}, while for both copper backing and water cooling h = 350 Wm^{-2} K^{-1}.

The upper boundary of the PMZ is the fusion boundary at the liquidus temperature T_L and the lower boundary of the PMZ is at the eutectic temperature T_E. Due to different cooling conditions, the temperature gradient $G_T = (T_L - T_E)/ W_P$ [3,10] in the fusion boundary varies, causing a change in the width of the PMZ (W_P).



(a) (b)

Fig. 5. Thermal profiles of SSM A356 TIG welded with different cooling conditions. (a) Copper backing, and (b) copper backing and water cooling.



(a) (b)

Fig. 6. SSM A356 TIG welded with different cooling conditions. (a) Copper backing and, (b) copper backing and water cooling.

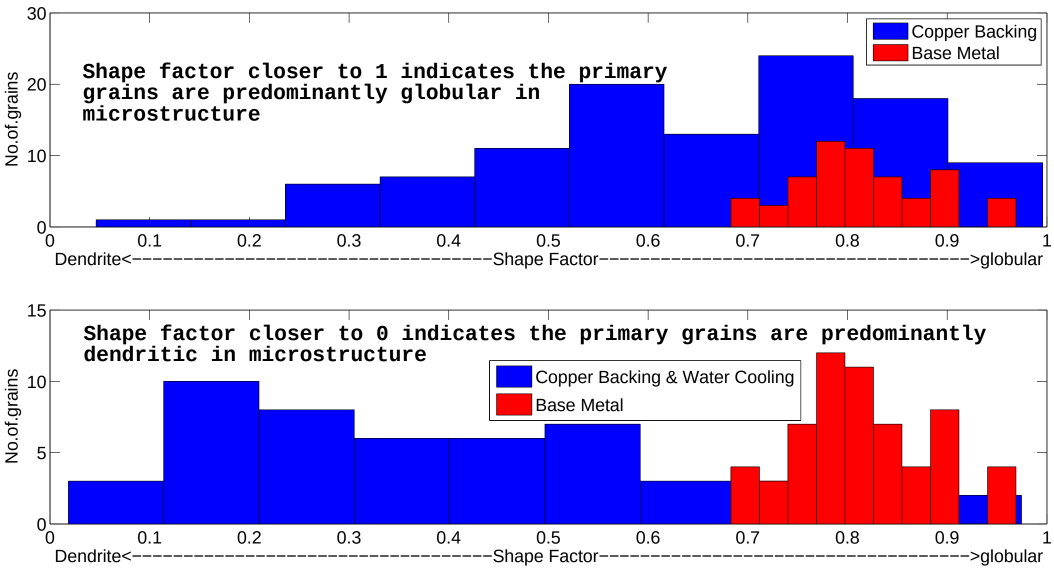


Fig. 7. Histogram of grain shape factors in FZ under different cooling conditions compared with the base metal.

The microstructures of the FZ of SSM A356 with copper backing (Fig. 6a) exhibited a more globular morphology than the FZ when welding was done with both copper backing and water cooling (Fig. 6b). The sample welded with a copper backing experienced a gradient of 25 K/mm and had a PMZ width of 0.709 mm. The sample welded with both a copper backing and water cooling experienced a gradient of 29 K/mm and the width of the PMZ was 0.348 mm. The higher width of the PMZ in the copper backing arrangement may be attributed to a greater number of loose grains, hence more nuclei, than that of the base metal, causing globular a microstructure in the FZ. In the case of both copper backing and water cooling, the thermal gradient is high which means a smaller width of PMZ, hence a low number of nuclei and more free growth for a dendritic microstructure. Micrographs taken at the centre of the FZ for various samples were used to calculate the shape factor of grains. From the histogram (Fig. 7) it is confirmed that samples TIG welded with a copper backing exhibit shape factors closer to that of base metal i.e. a globular microstructure, while the samples welded with both copper backing and water cooling exhibit predominantly dendritic growth.

Conclusions

Using simulations to quantify thermal gradients in the PMZ and quantitative metallography to quantify width of PMZ and globularity of a-Al grains, the following conclusions could be made.

1. The thermal analysis results showed a positive correlation of lower G_T i.e., higher W_P with a globular microstructure formation in semi-solid processed Al alloy A356.
2. The increase in thermal gradient due to faster cooling rate changes the solidification morphology from globular to dendritic microstructure in the FZ.

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