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Method for Laboratory-Scale Wedge Casting of Aluminum Alloys

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14. ABSTRACT A method for laboratory-scale permanent wedge mold casting of aluminum alloys was proposed and evaluated for its ability to provide a wide range of industrially relevant solidification behaviors for material property testing. Analysis of the cast microstructure of A356.0 (Al-7Si-0.4Mg) was performed via measuring the secondary dendrite arm spacing (SDAS) and correlated to well-known relationships between SDAS and solidification rate. Results showed that the wedge dimensions were capable of providing a range of nearly two orders of magnitude in solidification rate, which covers a range from permanent mold castings to die castings, thus validating the wedge mold dimensions.					
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1. Introduction

In modern materials science, there is currently a paradigm shift toward high-throughput materials processing and development for the discovery of novel materials. This includes use of computational materials science, machine learning/artificial intelligence–informed design, autonomous materials processing, and characterization among other methods.¹ For instance, thin film deposition can be used to create a compositional gradient of a material system on a single wafer, which can then be used to correlate local chemistry with material properties using microscale and nanoscale techniques. This is in stark contrast to conventional material development where numerous batches of materials are made to study variation in composition and/or material processing parameters. Each has advantages and disadvantages, but it is important that the alloy development scheme is representative of the manufacturing technique for end use.

The purpose of this investigation was to evaluate and develop a method for producing an array of microstructures with realistic solidification rates in a single batch process for an alloy composition of interest with industrial castings in mind. In this case, a wedge-shaped casting was evaluated on laboratory-scale castings to meet this objective.

2. Methods

In this investigation, A356.0 (Al-7Si-0.4Mg) was prepared by loading the appropriate proportions of 99.99% pure aluminum (Al) (Belmont Metals), 99.99% pure magnesium (Mg) (US Magnesium LLC), and 99.95% pure Al-25Si master alloy (American Elements) for a target mass of 1150 g in a high-purity graphite crucible. An Indutherm VTC 800 V/Ti vacuum induction melting and casting unit was used to melt and cast all wedge castings. The wedge mold pattern with dimensions as shown in Fig. 1 was machined from a 5-inch (127-mm)-diameter cylinder of commercially pure C110 copper (Cu) (UNS C11000, McMaster-Carr) to incorporate a wedge and riser sections to minimize shrinkage porosity within the dimensional restrictions of the VTC casting chamber. Final wedge mold dimensions were chosen iteratively using simulations of A356 within the MAGMASOFT software package. Initial melting of the alloy charge was made under atmospheric pressure of ultra-high-purity argon (Ar) gas after vacuum-pumping down the melt chamber below -1.00 bar for 3 min to remove oxygen for the melt chamber. As all of the required charge could not be loaded into the melting crucible, the remaining charge was added after initial melting, resulting in a mixture of Ar and atmospheric air. Castings were made under three different conditions as

shown in Table 1, where the melt was held at their respective pour temperatures for 10 min to ensure good electromagnetic mixing after all charge was melted. Molds were preheated for 4 h in a top-load kiln with a hold temperature +20 °C to that of the target mold temperature to account for mold heat loss during transfer from the kiln to the casting chamber via a chain hoist. After pouring, castings were allowed to furnace-cool for 1 h within the casting chamber before being removed from the mold and air-cooled to room temperature.

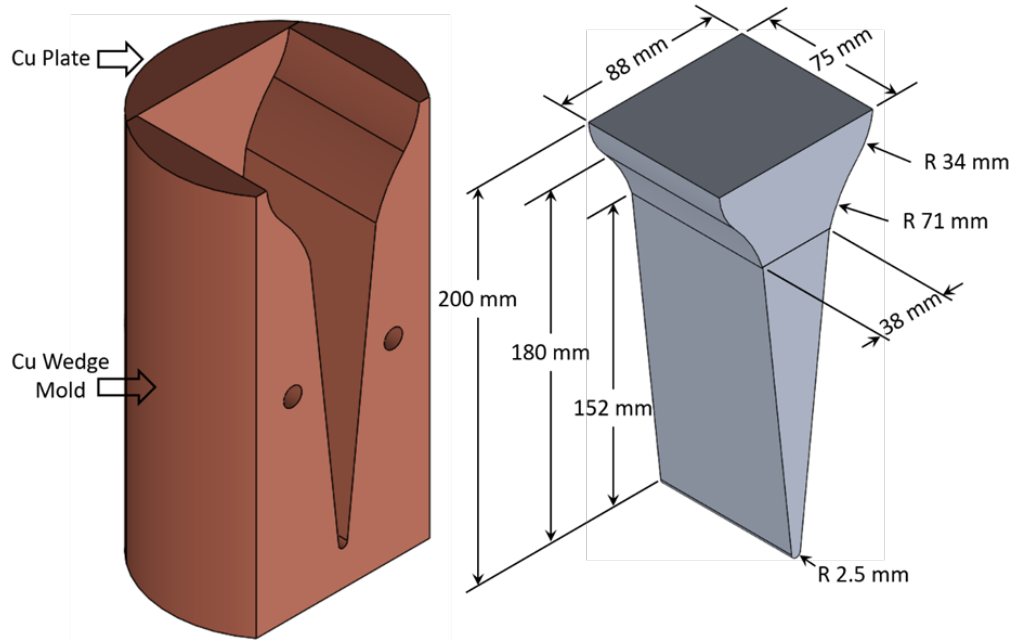


Fig. 1 Schematic of the wedge mold with front Cu plate removed and cavity dimensions used in this investigation

Table 1 Castings parameters

Cu mold target preheat (°C/°F)	Pour temperature (°C/°F)
23 / 73	810 / 1490
200 / 392	750 / 1382
400 / 752	750 / 1382

After casting, the riser section was cut off the castings, and the remaining wedges were cross-sectioned along the width for microstructural analysis. In this report, only the section with a thickness of 4 mm representing the center of each wedge casting was evaluated for microstructure. Evaluation of the wedge casting was first performed via macro etching in a freshly prepared solution of 53% v/v concentrated HCl, 29% v/v H₂O, and 18% v/v mL concentrated HNO₃. Prior to macro etching, samples were ground to a CAMI 600-grit finish while optical images of the etched surfaces were taken using a Cannon 9000F Mark II scanner. Samples for

microstructural evaluation were ground and polished to a 0.25- μm finish using an oil-based diamond-polishing suspension. Samples were then etched using a solution of 10 g/L NaOH and characterized using the optical lenses of a Keyence VK-X1000 3-D laser confocal microscope. SDAS measurement was performed using the FIJI software package for ImageJ by measuring the center-to-center distance among secondary dendrite arms along the primary dendrite and counting the number of secondary dendrites. The SDAS was then calculated using the equation

$$d = \frac{L}{N-1} \quad (1)$$

where d is the SDAS, L is the length of the dendrite cells, and N is the number of secondary dendrite arms counted along L . A schematic of this method is shown in Fig. 2.

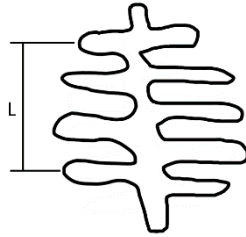


Fig. 2 Schematic of SDAS measurement where the distance L is measured from the center-to-center distance of secondary dendrite arms

3. Results

Optical images of the macro-etched structure of each mold preheat are shown in Fig. 3. From the captured images, two solidification zones are readily apparent: (1) a directionally solidified zone near the outer edges of the wedge and (2) an equiaxed zone in the middle of the wedge. Furthermore, the macro grain colony size increased with increasing mold preheat as higher mold preheat temperature decreases the degree of undercooling for solidification. This retards the cooling rate and promotes the growth of larger grains. Some microporosity was prevalent throughout the wedge zone, but most of the porosity was revealed below the shrinkage pipe of the riser as shown by cross-sectional images in Fig. 4. Near the tip of each wedge, it is apparent the grain size is very small, but the grain size increases with increasing thickness of the wedge as intended. This is shown more clearly by the optical images in Figs. 5–7 at different distances from the tip of the wedge.



Fig. 3 The macro-etched structure for center slices of wedges produced at different Cu mold preheats

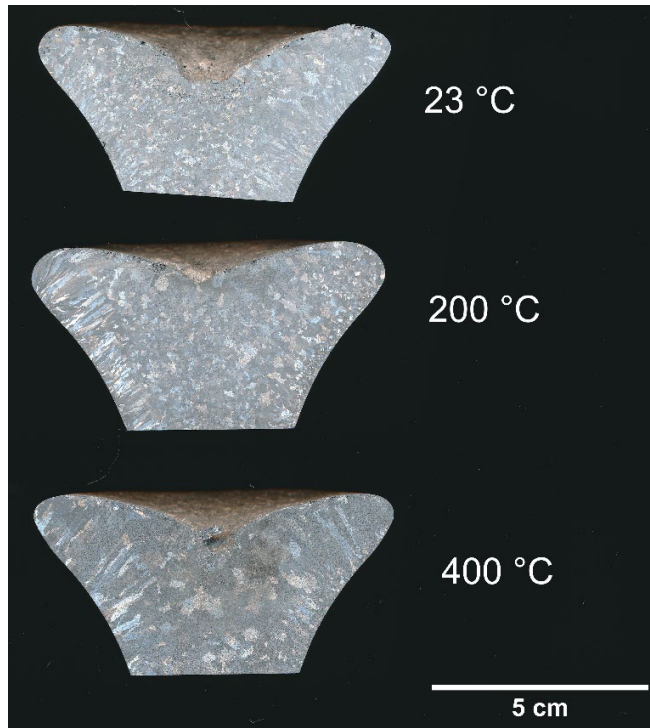


Fig. 4 The macro-etched structure of the riser at different Cu mold preheats cross-sectioned in half

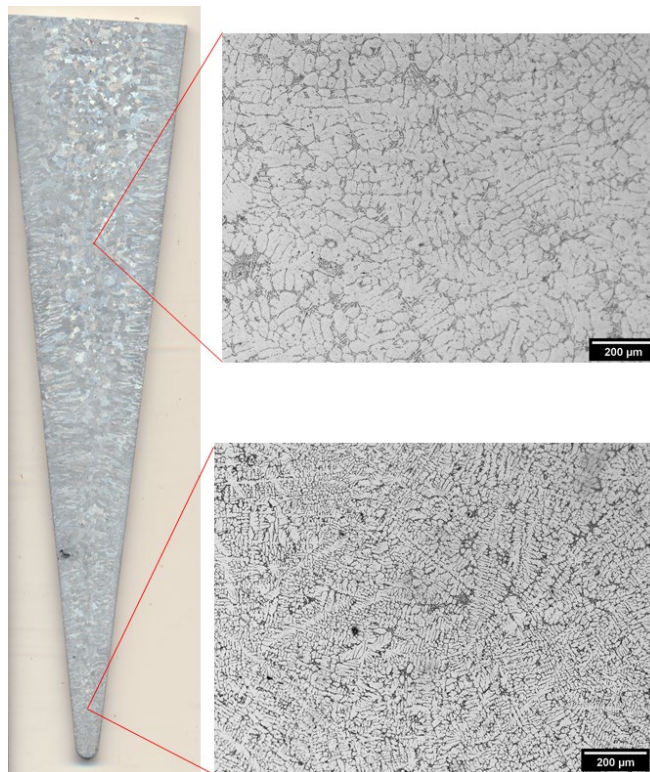


Fig. 5 Optical micrographs taken at different heights of a wedge slice with no preheat

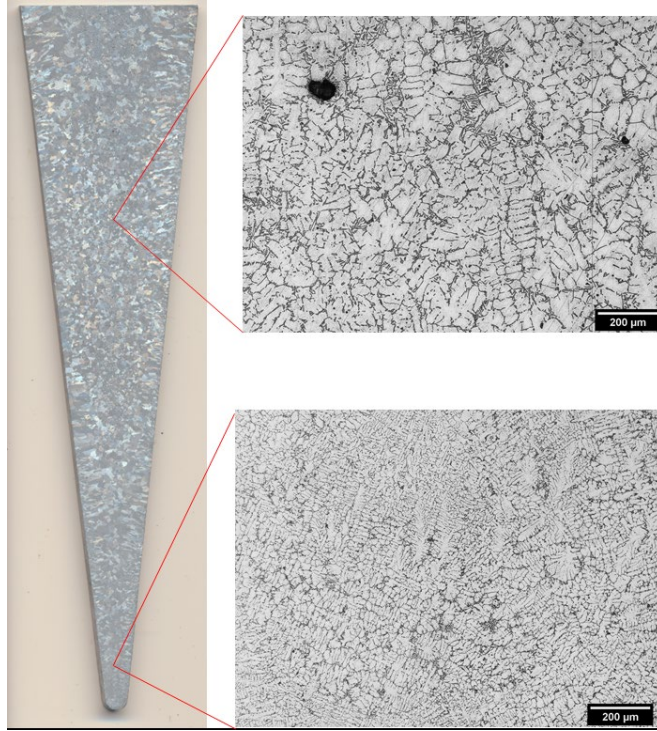


Fig. 6 Optical micrographs taken at different heights of a wedge slice for Cu mold preheat at 200 °C

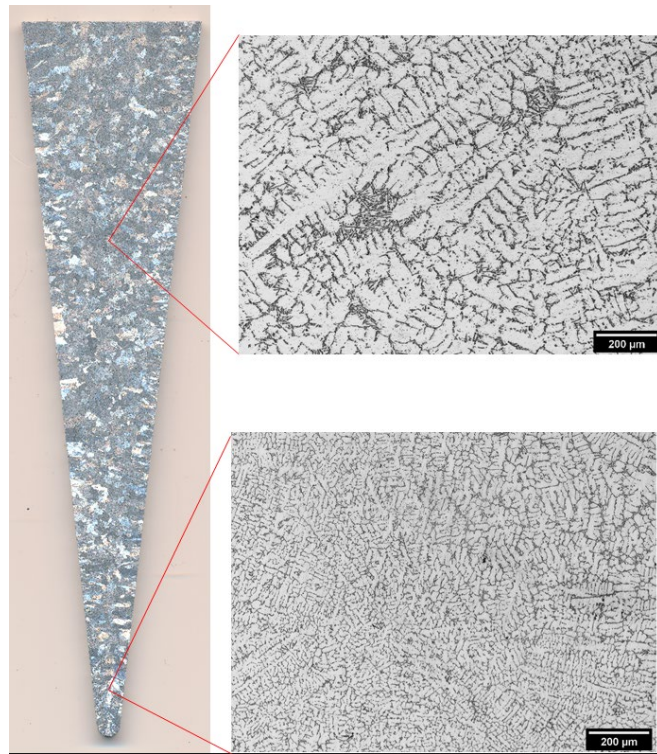


Fig. 7 Optical micrographs taken at different heights of a wedge slice for Cu mold preheat at 400 °C

Measurement of the SDAS as a function of distance from the tip of the wedge along its centerline is shown in Fig. 8, where the solidification rate is based off of values for an empirical relationship between SDAS and the solidification rate of Al alloys established by Spear and Gardner.² Linearization of the data was found to best fit a power-law relationship of the form

$$d = bx^n \quad (2)$$

where d is the SDAS in micrometers, b and n are constants, and x is the vertical distance from the tip of the wedge in centimeters. Fitting of the data using this equation reported in Table 2 shows very good correlation with Pearson R^2 values above 0.9, which means that the solidification gradient as a function of distance from the tip of the wedge is proportional to the relationship between SDAS and the solidification rate, which follows the same form power law.² Importantly, the estimated solidification rates based on the measured SDAS here show nearly a two order of magnitude difference, which is capable of covering a wide array of solidification technologies. In this case, the estimated solidification rate range covers from permanent mold to die castings but is too fast for typical sand castings.³ Nevertheless, this range of solidification rate is industrially relevant and can be used to evaluate the microstructure and material properties of novel alloys for a wide number of uses.

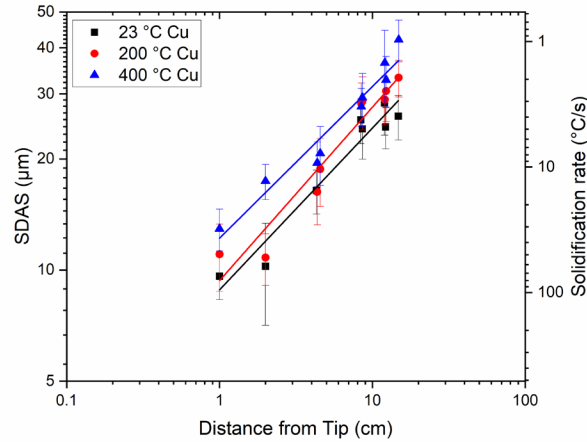


Fig. 8 Log-log plot of measured SDAS from the bottom tip of wedge castings with linear fit of the data. The solidification rate is estimated using the empirical equation determined by Spear and Gardner.²

Table 2 Values for regression fitting of SDAS vs. distance from the tip of the wedge using Eq. 2.

Cu mold preheat (°C/°F)	b	N	R^2
23 / 73	0.946	0.438	0.944
200 / 392	0.971	0.470	0.934
400 / 752	1.086	0.410	0.947

4. Conclusions

This investigation has documented a method for casting wedges of Al alloys for the study of varying solidification rates. The mold material, dimensions, and thermal parameters used here have validated wedge mold dimensions herein for the method's suitability to provide nearly two orders of magnitude difference in solidification rate, which will aid in cast alloy development.

5. References

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List of Symbols, Abbreviations, and Acronyms

3-D	three-dimensional
Al	aluminum
Ar	argon
Cu	copper
Mg	magnesium
SDAS	secondary dendrite arm spacing
VTC	vacuum tilt casting

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