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## ABSTRACT

The most popular aluminum alloys for semi-solid automotive components are A356 and A357. The density of rheocast semi-solid A357 is higher than die cast A357 and allows for both T5 and T6 heat treatment. The mechanical properties of rheocast semi-solid A357 was found to be more dependent upon the heat treat schedule and casting soundness than by the solid content of the semi-solid slurry or the globule shape.

## INTRODUCTION

Two casting technologies have been developed for producing semi-solid metal (SSM) components, thixocasting and rheocasting. In the thixocasting process, a solid billet, with a fine-grained equiaxed microstructure, is partially remelted to the semi-solid state. The billet is then transferred to the shot chamber of a die cast machine and injected into a die. Rheocasting involves stirring the alloy during solidification to produce a semi-solid slurry, then injecting the slurry directly into the die. These two fundamentally distinct approaches are illustrated in Figure 1.

The rheocasting process offers several advantages over thixocasting:

- Reduced process complexity – A multi-station heating system is not required, nor is a robotic transfer system.
- Increased shot size flexibility – There are no shot size restrictions related to the billet height to diameter ratio.
- Alloy modifications can be made in house.
- Solid fraction can be tailored to the application – Billets have a narrow solid fraction working range.
- Unrestricted metal suppliers – Die cast ingots are readily available from several sources and cost less than the specially prepared thixocasting billet.
- In house scrap recycling – Scrap can be remelted and used again, whereas in thixocasting, the metal must be returned to the supplier to be recycled into new billets.
- Lower cost, as compared to other semi-solid processes.

This paper will discuss the effect of processing on the mechanical properties of rheocast semi-solid A357 aluminum cast.

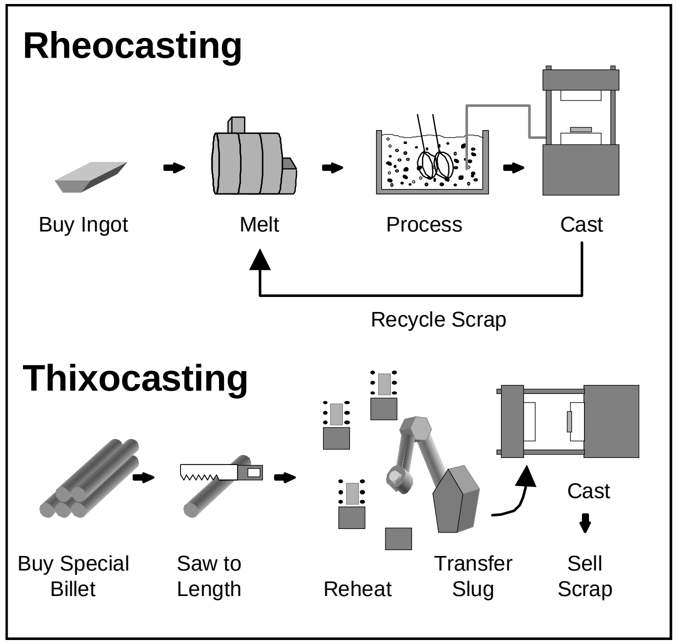


Figure 1. Schematic of the Rheocasting and Thixocasting processes.

## EXPERIMENTAL MATRIX

Rheocast half-inch diameter tensile bars (ASTM E8) were cast at various combinations (Shot Profiles) of solid fraction, shearing rate, and holding time as shown in Table I. The mechanical properties, density and microstructure were analyzed in the as-cast, T5 and T6 heat treated condition. An alpha-numeric designation was assigned each shot profile starting with the solid (5 to 25%) content of the slurry, followed by a letter to designate the shear rate (Low or High), and then the heat treat condition (A for as-cast, 5 for T5, or 6 for T6). Example: 25LA designates the shot profile 25% solid, low shear rate, as-cast condition.

Table I. Experimental Matrix

| Solid Content of the Slurry | Shear Rate | |
|---|---|---|
| | **Low** | **High** |
| **5%** | As-Cast, T5, T6 | As-Cast, T5, T6 |
| **10%** | As-Cast, T5, T6 | As-Cast, T5, T6 |
| **15%** | As-Cast, T5, T6 | As-Cast, T5, T6 |
| **20%** | As-Cast, T5, T6 | As-Cast, T5, T6 |
| **25%** | As-Cast, T5, T6 | As-Cast, T5, T6 |

The high shear rate level was approximately 1.67 times the low shear rate. The solid content of the slurry was controlled via the temperature of the furnace (±1 °C). Traditional tip lube was applied by hand every third shot and a squeeze cast die spray was used to minimize gas entrapment. The ram profile was not changed for the duration of the experiment, nor were the other casting parameters such as metal pressure and gate velocity.

## RESULTS AND DISCUSSION

CHEMISTRY – The most popular aluminum alloys for semi-solid automotive components are A356 and A357.[1-5] These alloys have a relatively high eutectic content and offer a range of mechanical properties when heat treated. The alloy chosen for this study was A357 aluminum with the chemical composition shown in Table II.

Table II. Chemical composition (Wt. %) of A357 alloy

| **Al** | **Si** | **Mg** | **Fe** | **Cu** | **Mn** |
|---|---|---|---|---|---|
| Bal. | 6.504 | 0.597 | 0.19 | 0.053 | 0.012 |

MICROSTRUCTURAL EVALUATION – A Princeton Gamma-Tech Imagist system was used to quantify the percent solid and globule circularity of the as-cast microstructure (Figure 2). Figure 3 shows the actual percent solid of the slurry compared to the predicted levels outlined in the experimental matrix. The correlation between the two is pretty good considering that chemistry variations, as allowed within the specification limits, will affect the liquidus temperature and thus, the fraction solid.

Circularity was measured to quantify the effect of shear rate and percent solid on the size, shape, and agglomeration of the globules. Circularity is defined as the square of the ratio between the maximum dimension of the feature divided by the area equivalent diameter of the feature. The area equivalent diameter is defined as the diameter of a circle with the same area as the feature. For a perfect circle the circularity would be one.

Figure 4 shows the circularity as a function of shot profile. The circularity appears unaffected by either shear rate or percent solid within the limits set in the experimental matrix.

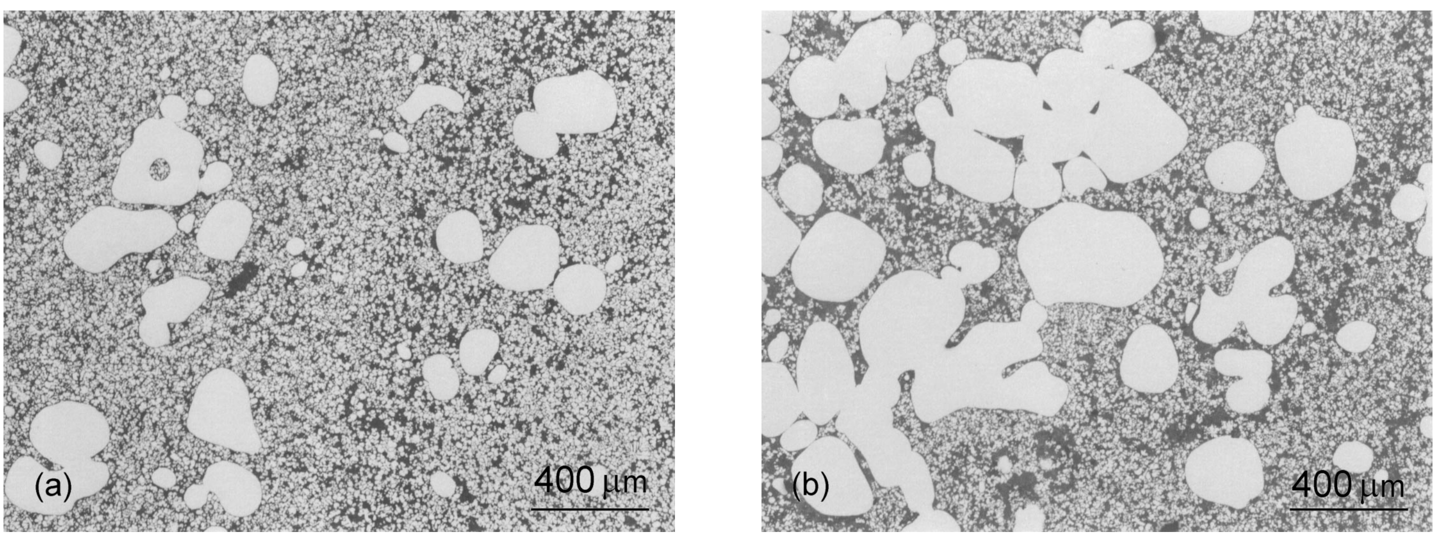


Figure 2. Typical microstructures of shot profiles (a) 5LA and (b) 25LA. The large white objects are the primary aluminum globules (Solid portion of the slurry). The surrounding matrix (Formerly, the slurry liquid) is composed of fine primary aluminum dendrites (White) and the eutectic phase (Dark).

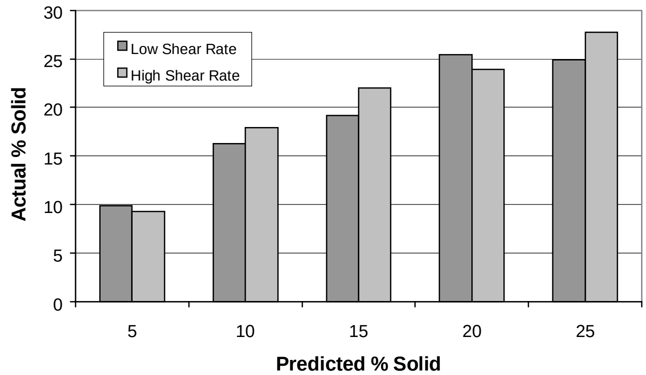


Figure 3. Solid content of the semi-solid slurry.

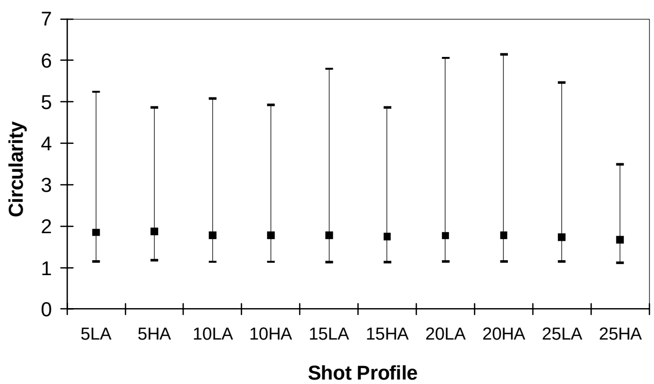


Figure 4. Globule circularity (Average and Range) as a function of shot profile.

DENSITY – The theoretical density ($D_{Th}$) of the material can be calculated using the rule of mixtures. This method predicts the density by adding together the density contributions of each element ($D_j$) relative to their weight fraction ($F_j$) according to the equation

$$D_{Th} = \frac{1}{\sum_{j=1}^{m} \frac{F_j}{D_j}} \tag{1}$$

The density of the tensile bars ($D_B$) can be determined by weighing the tensile bars dry and suspended in water according to the equation

$$D_B = \frac{M_D}{V} \tag{2}$$

where $M_D$ is the dry mass of the tensile bar and $V$ is the volume of the test bar. The volume of the tensile bar can be calculated according to the equation

$$V = \frac{M_D - M_W}{\rho_W} \tag{3}$$

where $M_W$ is the mass of the tensile bar suspended in water and $\rho_W$ is the density of water.

Figure 5 shows the calculated density of the various as-cast shot profiles compared to the theoretical density of 2.6703 g/cm$^3$ and the density of tensile bars cast with 100% liquid. The as-cast density of the semi-solid material does not appear to be a function of solid fraction and is significantly better than the liquid cast samples. The higher density is indicative of the lower porosity levels associated with semi-solid casting.

MECHANICAL PROPERTIES – One attractive feature of semi-solid A357 aluminum is that it can be given either T5 or T6 heat treatments. Table III lists the mechanical properties obtained with the rheocasting process in the as-cast, T5, and two different T6 conditions. The vastly different properties obtained with the two T6 heat treatments indicates that further study is required to find the optimal heat treat schedule.

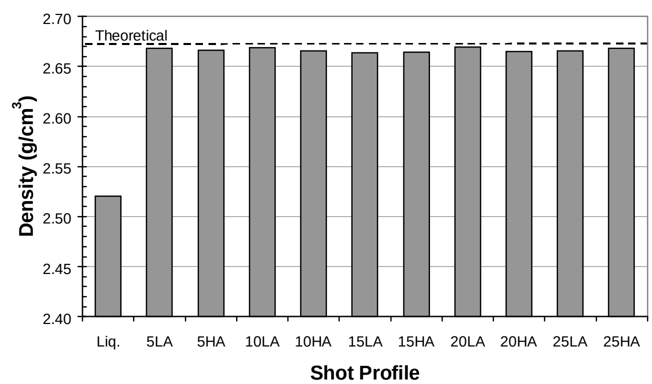


Figure 5. Casting density as a function of shot profile.

Table III. Mechanical Properties – A357 Aluminum.

| Casting Process | Heat Treat | Tensile Strength (MPa) | Yield Strength (MPa) | Elong. (%) |
|---|---|---|---|---|
| Rheocast (See Note) | A/C | 242-251 | 101-121 | 6.5-8.6 |
| | T5 | 238-256 | 121-134 | 4.7-9.4 |
| | T6(a) | 255-285 | 140-168 | 7.3-13.2 |
| | T6(b) | 335 | 281 | 4 |
| Thixocast [1,2,6-8] | A/C | 220 | 115-120 | 7-9 |
| | T5 | 275-290 | 200-210 | 5-10 |
| | T6 | 330-358 | 260-290 | 9-10 |
| Permanent Mold[9] | A/C | 193 | 103 | 6 |
| | T51 | 200 | 145 | 5 |
| | T6 | 359 | 296 | 5 |
| Sand Cast[9] | A/C | 172 | 90 | 5 |
| | T51 | 179 | 117 | 3 |
| | T6 | 345 | 296 | 2 |

Note: T5 [5 hrs @ 177°C]
T6(a) [4 hrs @ 529°C, Quench, 8 hrs @ 20°C, 4 hrs @ 154°C]
T6(b) [12 hrs @ 529°C, Quench, 8 hrs @ 20°C, 6 hrs @ 154°C

Figure 6 shows the ultimate tensile strength, the yield strength, and percent elongation as a function of shot profile, in the as-cast condition. The ultimate tensile strength appears to be independent of the shot profile. The as-cast yield strength and percent elongation possibly show some sensitivity to percent solid, with the yield strength increasing and the percent elongation decreasing as the percent solid increases. This trend is not strong enough to be considered significant.

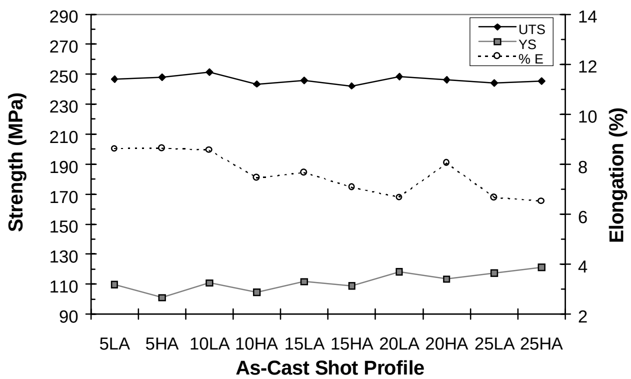


Figure 6. Ultimate tensile strength (UTS), yield strength (YS) and percent elongation (% E) as a function of shot profile for the as-cast condition.

The ultimate tensile strength, yield strength, and elongation appear to be independent of shot profile in the T5 condition, as shown in Figure 7. There does appear to be more variation in the elongation data.

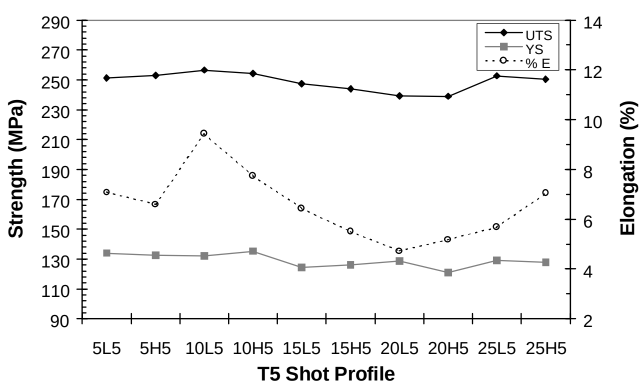


Figure 7. Ultimate tensile strength (UTS), yield strength (YS) and percent elongation (% E) as a function of shot profile for the T5 condition.

The ultimate tensile and yield strengths are also independent of shot profile in the T6 condition, as shown in Figure 8. The elongation decreases significantly at solid contents of 15% and higher. This decrease is related to the density of the samples in the T6 condition.

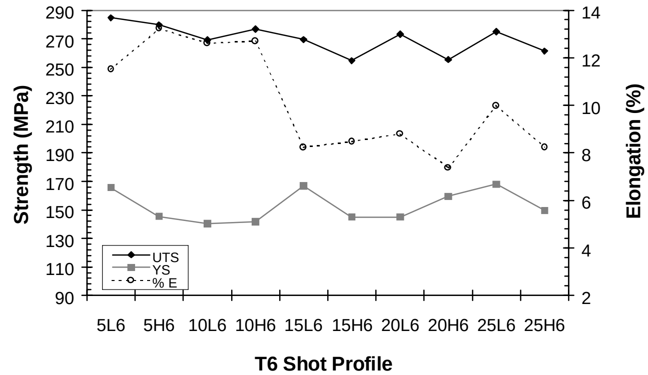


Figure 8. Ultimate tensile strength (UTS), yield strength (YS) and percent elongation (% E) as a function of shot profile for the T6 condition.

Figure 9 shows the correlation between density and elongation, as a function of T6 shot profile. The decrease in density, at solid contents of 15% and higher, is most likely related to the type of porosity in the test specimens. There are two types of porosity associated with the die casting process. That which forms as the liquid solidifies (shrinkage porosity) and that associated with gas entrapped during the casting process. Shrinkage porosity decreases with increasing solid content, as there is less liquid to solidify. Seeing that the density was relatively constant across all the as-cast profiles, the amount of entrapped gas porosity must have increased to balance the decrease in shrinkage porosity. The density of the T6 samples thus decreases as the gases expand during heat treatment. The most likely source of the gas porosity was the tip lube or the die spray.

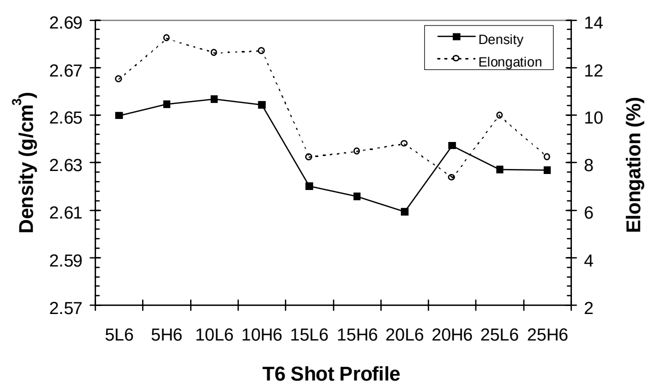


Figure 9. Density – Elongation relationship in the T6 condition.

## CONCLUSIONS

- The density of rheocast semi-solid A357 is higher than conventional die cast A357 and allows for both T5 and T6 heat treatment.

- The mechanical properties are more dependent upon the heat treat schedule and casting soundness than by the percent solid prior to casting or the globule shape.
- The consistency of the microstructure and mechanical properties over the entire test matrix shows the process to be a robust manufacturing process.

## ACKNOWLEDGMENTS

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