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Publisher's version / Version de l'éditeur:

Proceedings. Shape Casting: 4th International Symposium 2011 in honor of Prof. John T. Berry, pp. 273-281, 2011

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Optimization of the process parameters and tooling improvement for the rheocasting of high quality aluminum components using the SEED process

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Keywords: rheocasting, aluminum, SEED process, semi-solid, semi-solid casting, HPDC

Abstract

The automotive industry has leaned greatly towards the use of aluminum alloys by virtue of their strength and low density. Given this, the potential for aluminum use in the fabrication of vehicle parts has greatly increased. However, there are limited studies devoted to the improvement of the casting process. In the present work, the SEED (Swirled Enthalpy Equilibrium Device) rheocasting method, as developed by Rio Tinto Alcan in collaboration with the Aluminium Technology Center of NRC Canada (ATC-NRC), was analyzed by the authors in an attempt to optimize operating parameters (e.g. proper mold filling, slurry temperature, injection speed, etc.), which affect the final cast part quality. In many of the existing semi-solid casting processes which use billets as feedstock, for example, it is often found that the outer surface of the billets is contaminated. During the injection phase, a billet's external skin comes into contact with air and lubricant, and, as a result, becomes contaminated. The use of such a contaminated billet can often result in an increased rejection rate of cast parts. The SEED process, which uses heat extraction of the liquid aluminum alloy via mechanical agitation (swirling) in a confined cylinder to form the semi-solid billet on site, has already proven successful in producing sound aluminum castings having an excellent combination of strength and ductility. The resulting semi-solid billet, having a microstructure consisting of α -Al globules surrounded by the eutectic phase, is then injected into the cold chamber of an HPDC machine.

Introduction

Conventional shape casting processes such as pressure die casting, for example, offer both low cost and high productivity. The downside, however, is that pressure die-cast parts are generally prone to fabrication defects and limited mechanical properties [1]. One possible remedy is semi-solid pressure die casting, which can yield quality parts comparable to those made with wrought processes; the cost of casting is comparable to using conventional pressure die casting. Indeed, semi-solid pressure die casting can eliminate casting defects and allow for additional improvement, such as the use of heat treatments, to the production process [2, 3]. Within the framework of a collaborative effort between Rio Tinto Alcan and ATC-NRC, studies were carried out to assess the performance of a 357 alloy designed for semi-solid pressure die casting and improve casting tooling design which, in turn, helps to improve mechanical properties; these studies are based on a new design of experiment (DOE) method that builds on experience, *i.e. the Expectation-Maximization (EM) Method*. The semi-solid billets were prepared using the SEED process [4], as shown in Figure 1.

Figure 1. SEED process of Rio Tinto Alcan [3].

This patented method [5] employs the heat extraction of the liquid aluminum alloy via swirling, in a confined cylinder. The resulting semi-solid billet is injected into an HPDC press to yield quality parts. A proper set of working parameters can lead to a uniform and globular microstructure which, in turn, can decrease slurry viscosity and improve die filling; likewise, an improper use of these parameters can result in defects, and reduced mechanical properties [6, 7].

Methodology

In the DOE, the EM Method was used to keep the number of tests to a minimum. This consists of: (i) defining parameters (factors and responses) and objectives, (ii) conducting experimental tests and building operational domains, (iii) regressions and building models, (iv) validation and (v) multi-criteria optimization, which consists in maximizing a desirability function that expresses the importance of combined criteria in relation with targeted goals. A direct research method is then applied to find optimal solutions [8, 9]. The operational domain, in a multi-dimensional space, is modeled as an ellipsoid (Figure 2) and defined with continuous values, which discriminate between accepted tests (inside) and rejected tests (outside). This is not to say that the test points which do not fit inside the operational domain are discarded from the work, rather they are not included in the ellipsoid. However, they are still used in the overall model. Test points have coordinates (a, b, c, d, e...), which change with the number of operational parameters (i.e. factors) being considered.

Figure 2. Simplified view of the multidimensional operational domain, modeled as an ellipsoid.

Because this ellipsoid is a crude representation of the operational domain, perfect discrimination between all the accepted and rejected points is not always possible. Usually, limitations and constraints on the factors truncate the ellipsoid, contributing to a more realistic shape of the operational domain. For this work, the 'EM Optimization' software by EM Optimization International Inc. was used.

Semi-solid 357 aluminum alloy wedge plate parts (Figure 3) were cast using the SEED process highlighted in Figure 1, with a 530-tonne HPDC press. These plates were subsequently subjected to a T6 heat treatment consisting of (i) a solution heat treatment of 540°C for 6 hours, (ii) a 20°C water quench and (iii) an aging step of 170°C for 6 hours. Following this, ASTM B557 round bar tensile samples, with a gage length of 25 mm and a gage diameter of 6.35 mm, were machined at pre-assigned locations along the plate length (Figure 4).

Figure 3. Schematic of the cast wedge plate.

Figure 4. Position of tensile samples and hardness test points on the cast wedge plate.

For simplicity, we will only consider the results obtained for section A (Figure 4). In other words, the mechanical properties such as yield strength, ultimate tensile strength, etc. will all be measured from tensile samples taken at position A. Standard liquid metal treatment and control steps were applied to the aluminum in the furnace, e.g. chemical composition check, rotary fluxing, degassing, etc.

Results and Discussion

In this work, 13 parameters (seven factors and six responses) were considered. These are listed in Tables 1 and 2 for factors and responses, respectively. Figure 5 illustrates the scanned area used for measuring the average α -Al globule size. In this work, 55 castings were produced. Of these, 34 met the pre-established ranges. The distribution of these 55 test points is relatively uniform inside the operational domain (Figure 6). Regression models, based on the tests carried out, were established to quantify the effects of the working parameters on the responses.

Table 1. Factors and their typical range.

Factors		Range
A	Pre-filling speed	0.5-1.0 m/s
B	Filling speed	0.2-1.4 m/s
C	Intensification pressure	900-1100 bar
D	Die temperature	169-260°C
E	Metal pouring temperature	630-645°C
F	Sr concentration	0-100 ppm
G	Drained mass	80-270 g

Table 2. Responses and their typical range.

Responses	Definition	Range
Yield strength	The value of the yield strength obtained at section A.	250-280 MPa
Ultimate tensile strength	The maximum value of the tensile stress recorded at section A.	275-355 MPa
Percent elongation	A measure of the ductility recorded at section A.	5-16%
Average α -Al globule size	A measure of the average value of the width of α -Al globules near the fracture area at section A, from image analysis; scanned area measures 10x6.35 mm (Figure 5).	50-75 μ m
Average part hardness	A measure of the average hardness value of 12 points on the plate surface, for each plate (Figure 4).	60-80 BHN
Part density	A measure of the density of the part, to illustrate the amount of porosity in the plate.	2.68-2.70 g/cm ³

Figure 5. Scanned section tensile sample for average width value (μ m) of α -Al globules.

Figure 6. Operational domain and test distribution (total of 55 tests).

Figure 7 demonstrates the degree of influence of the factors on a given response - in this case, the yield strength at section A. These effects are normalized, and shown in terms of being either positive (moving to the right) or negative (moving to the left). The greater a factor's influence (either positive or negative) on a response, the longer the red bar is in the histogram of Figure 7.

Figure 7. Factors and their relative impact on the yield strength (at section A).

According to Figure 7, Sr concentration (factor 'F') has the most influence on the yield strength, while filling speed ('B') has the least. Die temperature (factor 'D'), on the other hand, has no effect, as it is not shown in the histogram. There is an interaction between filling speed ('B') and intensification pressure ('C'), as well as pre-filling speed ('A') and drained mass ('G'). Figure 8 illustrates the behaviour of the yield strength response in more detail. The interactions demonstrate that the effect of factors C and A, for instance, are only significant when they are combined with B and A, respectively. In other words, the relationship is proportional, rather than linear (as in the case of Sr concentration) or squared (as in the case of the metal pouring temperature).

Figure 8. Yield strength at section A relative to filling speed, metal pouring temperature, drained mass, Sr concentration and die temperature.

It can be seen from Figure 8 that the yield strength: (i) increases from 277 to 282 MPa as the filling speed increases from 0.2 to 1.4 m/s, (ii) decreases, but then increases, as the metal pouring temperature increases (note that the curve is not linear like the others, owing to the E^2 relation shown in Figure 7), (iii) decreases from 292 to 269 MPa as the Sr concentration increases from 30 to 100 ppm, (iv) decreases from 287 to 270 MPa as the drained mass increases from 80 to 268 g, and (v) remains constant at all die temperatures tested. These observations can likewise be

made by considering the behaviour of any of the other responses (ultimate tensile strength, elongation, etc.) with respect to the effects of the working parameters. Histograms similar to Figure 7 are presented in Figure 9, for the remaining responses. It can be seen here, for example, that the Sr concentration greatly affects the percent elongation, α -Al globule size and density. On the other hand, the die temperature has little effect on the percent elongation or the hardness.

Figure 9. Relative impact of operational parameters (factors) on responses.

As can be seen from Figures 7 to 9, the regression models derived from the multi-dimensional analysis show the degree of influence of the operating parameters (factors) on the alloy's mechanical properties, microstructure (by measurement of primary α -Al phase size) and porosity defects (by density measurement). The overall influence of the operational parameters on the responses studied in this work is fully summarized in Table 3.

Table 3. Effects of operating parameters (factors) on responses.

		Factors						
		Pre-filling speed	Filling speed	Intensification pressure	Die temperature	Metal pouring temperature	Sr concentration	Drained mass
Responses	Yield strength	/	/	/	--	\	\	\
	Ultimate tensile strength	--	/	\	/	\	\	\
	Percent elongation	--	--	--	\	\	/	\
	α -Al globule size	--	\	/	\	\	/	/
	Hardness	--	\	\	\	/	\	--
	Density	\	/	--	--	\	/	\

/ = positive effect, \ = negative effect, \ = combined effect, -- = no effect, = less significant effect

According to Table 3, it can be observed that: (i) the prefilling speed has no significant effect on the majority of the responses, (ii) the filling speed has a significant effect on hardness, (iii) the intensification pressure has a significant effect on ultimate tensile strength and hardness, (iv) the die temperature has a significant effect on percent elongation and α -Al globule size, (v) the metal pouring temperature has a significant effect on yield strength, ultimate tensile strength and density, (vi) the strontium concentration has a significant effect on yield strength, percent elongation, α -Al globule size and density, and (vii) the drained mass has a significant effect on all of the responses, except hardness.

Multi-criteria optimization was used to maximize the mechanical properties (yield strength, ultimate tensile strength and elongation) all at once, in order to improve the performance of the parts being cast. One best solution point inside the feasible domain was found using the EM Optimization software, based on the models (Figure 10).

Figure 10. Optimization by EM software and the best solution found. The end point (i.e. best solution) has coordinates (A, B, C, D, E, F, G), which correspond to the optimized values of the working parameters.

Subsequent to the maximization of the mechanical properties, 50 wedge plate parts were produced with these optimized parameters, in order to provide the best possible solution (i.e. the best quality parts). In order to ascertain the quality of these optimized plates, once again, ASTM B557 tensile samples were machined and testing resumed. The results obtained for this optimized set of tensile samples are presented in Table 4.

Table 4. Optimized parameters and results.

Operational parameters (factors)		Optimized value		Predicted value using EM Method	Average value from tensile tests
A	Pre-filling speed (m/s)	1.0	Response at section A		
B	Filling speed (m/s)	0.46			
C	Intensification pressure (bar)	900			
D	Die temperature (°C)	260	Yield strength (MPa)	301	297 ± 4
E	Metal pouring temperature (°C)	630	Ultimate tensile strength (MPa)	353	350 ± 3
F	Sr concentration (ppm)	30	Elongation (%)	10.7	8.3 ± 0.8
G	Drained mass (g)	147			

As can be seen from Table 4, the predicted and observed values of the mechanical properties (yield strength, ultimate tensile strength and percent elongation) are in good agreement. Moreover, it is clear from these results that the alloy demonstrates very favourable mechanical property values, in terms of strength and ductility.

Conclusions

1. After having tabulated the effects of the working parameters on the responses, it was found that the yield strength is mainly influenced by pouring temperature, Sr concentration and drained mass. Moreover, the ultimate tensile strength is mainly influenced by pouring temperature, intensification pressure and drained mass, and the elongation is mainly influenced by die temperature, Sr concentration and drained mass.

2. After having carried out 55 tests, the optimum operating parameters for the 357 alloy in this work were obtained. With this information in hand, a new batch of 50 optimized parts were cast resulting in mechanical (tensile) property values which were in good agreement with the values predicted by the EM Method.
3. The average mechanical (tensile) property values (yield strength = 297 ± 4 MPa, ultimate tensile strength = 350 ± 3 MPa and percent elongation = $8.3 \pm 0.8\%$) obtained in this study demonstrate a very favourable combination of strength and ductility. These properties are attributed to the uniformly globular microstructures obtained using the SEED process, which result in high integrity castings and exceptional values of mechanical properties.

Acknowledgements

The authors acknowledge National Research Council Canada for the support and permission to publish. The authors wish to express special thanks to Mr. Dany Drolet, Ms. Geneviève Simard and Ms. Marie-Eve Larouche at the Aluminum Technology Centre of NRC Canada. Thanks also to our collaborators at Rio Tinto Alcan R&D in the SEED development Mr. Alain Lemieux.

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