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ARCHIVES
of
FOUNDRY ENGINEERING

DOI: 10.2478/afe-2013-0048

Published quarterly as the organ of the Foundry Commission of the Polish Academy of Sciences

VERSITA

ISSN (2299-2944)
Volume 13
Issue 2/2013

113–116

Optimization of Squeeze Parameters and Modification of AlSi7Mg Alloy

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Received 26.02.2013; accepted in revised form 07.05.2013

Abstract

The paper present the examination results concerning mechanical properties of castings made of AlSi7MG alloy in correlation both with the most significant squeeze casting parameters and with the modification treatment. Experiments were planned and held according to the 2^3 factorial design. The regression equations describing the influence of the squeeze pressure, the mould temperature, and the quantity of strontium modifier on the strength and elongation of the examined alloy were obtained. It was found that the main factor controlling the strength increase is the squeeze pressure, while the plasticity (A_5) of the alloy is affected most advantageously by modification. The application of modification treatment in squeeze casting technology enables for production of the slab-type castings made of AlSi7Mg alloy exhibiting strength at the level of 230 MPa and elongation exceeding 14%.

Keywords: Mechanical properties, Al alloys, Squeeze casting technology, Modification

1. Introduction

Squeeze casting technology belongs to the group of modern casting methods applied mostly to the aluminium alloys, which allow for production of high-quality castings with smooth surface, high dimensional accuracy and good shape fidelity, and which simultaneously are characterised by the low production costs as well as material and energy savings. Among the advantages of the method one can also mention the high tightness, fine grain structure, the lack of surface defects, high productivity of the process, high metal yield (up to 98% of liquid metal) and small machining allowances. Squeeze casting combines the three most important and most popular technologies of metal processing – die casting, pressure casting and forging. As far as the quality of castings is concerned, squeeze casting exhibit advantages over both die casting and pressure casting technologies, while it surpasses die casting and forging with respect to the economic factors. Squeeze casting is used for production of car rims, compressor and electrical engine cases, hydraulic elements working under high pressure, etc. [1-6].

Squeeze cast products exhibit also high mechanical properties, which values often exceed the values reached by plastically worked elements. The strengthening of cast alloys results here from the fine grain structure formed under the conditions of pressure applied during the solidification [3-7]. The continuous pressure applied during solidification increases thermal conductivity and eliminates the shrinkage gap, by the same lessening thermal resistance and increasing the supercooling of the alloy and the number of generated crystallization nuclei [4,9]. The degree of supercooling of the liquid metal is related to the squeeze temperature. The most effective way of availing pressure is to apply it at the temperature close to the solidification point [4,9]. Then the maximum alloy supercooling and the highest increase of nucleation rate occur. On the other hand, too large overheating can almost completely nullify the effect of the increased pressure. The high pressure suppresses also generation of gas bubbles within a casting, eliminating shrinkage macro- and micro-porosity, and increasing density and plasticity of die stampings [10,11]. Pressure is a thermodynamic parameter affecting significantly phase transitions. As far as the two-component Al-Si alloys are concerned, an increased pressure results in a higher equilibrium solidification temperature of aluminium and decreased solidification temperature of silicon, according to the Clapeyron-Clausius equation. As a result, the eutectic point moves towards higher silicon contents. During the solidification of a squeeze cast item there occurs an increase in the growth rate of the α solid solution dendrites as well as the rise in the volume percentage of this phase in the structure. Simultaneously, regions enriched with silicon appear within the melt, thus enabling its crystallization in the shape of primary crystals [2, 12].

Thus the mechanical properties of squeeze cast products made of silumins depend on a series of physical and chemical phenomena occurring in the course of crystallization. In turn, the proceeding of these phenomena can be controlled mainly by the proper selection of Al-Si alloy grade, its modification, and technological parameters of squeeze casting. The problem of modification of silumins intended for die casting and casting in sand moulds is well-known and described in details in many publications [13, 15], whereas the effectiveness of modification process in squeeze casting technology is still rather insufficiently recognised [16]. Therefore the examinations were held in order to determine the relationship between mechanical properties of a slab-type casting made of the AlSi7Mg alloy and the most significant squeeze casting parameters (i.e. the pressure and the temperature of the mould) along with the modification treatment applied during its production. The initial optimization of variables was performed on the basis of the 2^3 factorial design.

2. Material and the examination method

Examinations were performed for standard AlSi7Mg alloy (PN-EN 1676). The melting of AlSi7Mg ingots was accomplished in the PIT50S/400 induction crucible furnace. The slab-shaped castings of dimensions 200 mm×200 mm×25 mm were obtained by means of the PHM-250c hydraulic press. The die was composed of two parts: the upper one (the punch) connected with the press ram, and the lower one, equipped with the ejector plate used for removing castings from the die. The machine was operated via the control panel, and the pressure was exerted by the hydraulic system.

During the squeeze casting process, first the die was coated with an insulating and lubricating layer. The colloidal solution of graphite in water was applied for this purpose. Then the die was heated to the appropriate temperature value (see Table 1). Next a portion of about 1350 g of molten metal was taken from the furnace crucible with the casting ladle and poured into the lower half of the die. Next the punch was lowered, the die was closed and the selected pressure applied (Table 1). The squeeze time was constant and equal to about 50 seconds. After that time the upper part of the die was lifted up and the casting was ejected by four ejector pins placed in the corners of the slab. A series of castings was produced, each time for different set of parameters according to the design of the experiment. The thicknesses of obtained slab castings were slightly varied due to the lack of precision dosage of the molten metal. The examinations were performed both for the non-modified alloy and for the one modified with AlSr10 strontium master alloy added in the shape of rods, 10 mm in diameter. The modification treatment was performed at constant temperature equal to about 720°C, then the molten alloy was held for 15 minutes and cooled down to the pouring temperature of 680°C. The quantity of added strontium modifier and the level of its change is shown in Table 6.

The fixed die mounted on the hydraulic press was also used for producing a series of common die castings. This was done by pouring the portion of metal into the die and then lowering the punch so that its surface touched the surface of molten metal in the lower die. The punch movement was stopped as soon as the contact was achieved, and the pressure was taken off. After solidification and cooling of a casting, it was removed from the die with the help of the ejection plate.

The examinations of mechanical properties were held for standard specimens with gauge length-to-diameter ratio of 5:1, according to the PN-EN 10002-1:2001 Standard, by means of the ZWICK-1488 servo-hydraulic tensile testing machine.

3. Results and the analysis of the experiment

Experiments were designed and accomplished according to the 2^3 factorial design, assuming the following independent variables and ranges of their change:

The independent variable, X_i	Centre point, X_{i0}	Range of change, ΔX_i
X_1 – squeeze pressure, MPa	30.1	30
X_2 – temperature of the die, °C	170	70
X_3 – quantity of modifier, %	0.02	0.02

The variables were coded according to a relationship:

$$x_i = \frac{X_i - X_{i0}}{\Delta X_i} \qquad (1)$$

The factorial design applied during the experiment gives a possibility to determine the incomplete quadratic equation describing the influence of the independent variables on the tensile strength and unit elongation of castings. The general form of the equation is:

$$\hat{y} = b_0 + \sum b_i x_i + \sum b_{ij} x_i x_j \qquad (2)$$

where:
b_0, b_i, b_{ij} – regression coefficients.

The full design, realised for all combinations of variations at their low levels, high levels, and centre points, is presented in Table 1. This table contains also the average results of both tensile strength and unit elongation measurements. A series of three experiments for the centre points (Table 1, rows 9-11) was completed to achieve the full statistic evaluation of the results. Statistic calculations done for the purpose of the factorial design realisation included variance analysis, calculation of the values of regression coefficients, evaluation of their statistic significance and checking the adequacy of regression equations. These calculations lead to the explicit formulas describing the change of the average tensile strength and the average unit elongation of castings for the independent variables within their examined range, i.e. respectively:

$$\hat{R}_m = 185{,}5 + 27{,}7\left(\frac{X_1 - 30{,}1}{30}\right) + 6{,}2\left(\frac{X_2 - 170}{70}\right) + 12{,}5\left(\frac{X_3 - 0{,}02}{0{,}02}\right) \quad (3)$$

and

$$\hat{A}_5 = 8{,}85 + 1{,}77\left(\frac{X_1 - 30{,}1}{30}\right) + 0{,}50\left(\frac{X_2 - 170}{70}\right) + 3{,}05\left(\frac{X_3 - 0{,}02}{0{,}02}\right) - 1{,}35\left(\frac{X_2 - 170}{70}\right)\left(\frac{X_3 - 0{,}02}{0{,}02}\right) \quad (4)$$

Table 1.
The applied design of experiment along with responses of the average tensile strength and the average unit elongation

	Independent Variables			Responses	
	Pressure [MPa]	Temp. of the mould [°C]	Quantity of modifier [%]	Average tensile strength R_m [MPa]	Average elongation A_5 [%]
	X_1	X_2	X_3		
Centre point	30,1	170	0,02	-	-
Range ΔX_i	30	70	0,02	-	-
High level (l)	60,1	240	0,04	-	-
Low level (-1)	0,1	100	0,00	-	-
Symbol of coded variable	x_1	x_2	x_3	-	-
Number of Experiment					
1	1	1	1	235,4	14,2
2	-1	1	1	173,7	10,6
3	1	-1	1	220,4	13,6
4	-1	-1	1	162,6	9,2
5	1	1	-1	204,9	7,8
6	-1	1	-1	153,0	4,8
7	1	-1	-1	192,0	6,9
8	-1	-1	-1	142,0	3,7
9	0	0	0	204,4	10,2
10	0	0	0	198,5	10,6
11	0	0	0	191,2	9,7

The Equation 3 indicates that the tensile strength is a linear function of each of the examined parameters of production, and it is the squeeze pressure which affects the strength most significantly. The equation coefficients for the particular variables show that the influence of pressure exceeds twice the influence of the Sr modifier and is four times greater than those of mould temperature. The influence of the examined independent variables on the tensile strength of a casting is illustrated in Figure 1. Positive coefficients at x_1, x_2, and x_3 denote that an increase in this parameters yields an increase in the tensile strength, while the lack of the combined influences x_1x_2, x_2x_3, x_1x_3 means that they are statistically not significant.

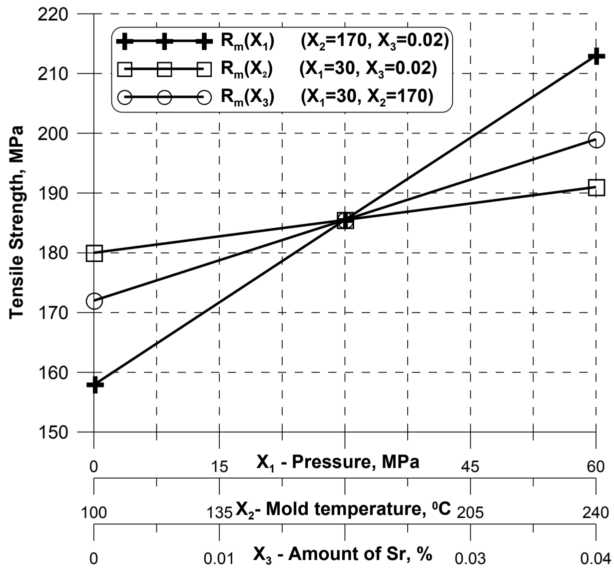

Fig. 1. The influence of squeeze pressure, mould temperature, and quantity of modifier on the tensile strength of castings made of AlSi7Mg alloy

The obtained formula and diagrams in Fig. 1 indicate that the increase in pressure by 10 MPa results in the R_m increased by about 10 MPa, while the rise in temperature by 100°C yields the growth of R_m by about 9 MPa. The addition of Sr modifier in the quantity of 0.01% of the AlSi7Mg alloy increases R_m by about 6 MPa.

Equation 4 shows that the unit elongation depends also on each of the three parameters of production, but it is most significantly influenced by the quantity of modifier added to the alloy. The strontium modifier affects the alloy elongation almost twice as much as the squeeze pressure and almost six times greater than the mould temperature. Also in this case all linear coefficients are positive, i.e. an increment in each variable increases the elongation. In the Equation 4, however, the term x_2x_3 occurred to be statistically significant and the value of the b_{23} coefficient is negative. It means that the combined influence of the mould temperature and modifier leads to the decrease in elongation for two cases: when both variables take their high level values or when both are at their low level. In other words, both the high temperature of the mould combined with the high quantity of modifier and the low temperature of the mould combined with the lack of modification decrease the plasticity of the examined silumin casting. The increase in squeeze pressure by 10 MPa results in the increase of A_5 by about 0.6%, the mould temperature raised by 100°C increases A_5 by about 0.35%, and the addition of modifier in the quantity of 0.01% increases A_5 by about 1.5% (Fig. 2).

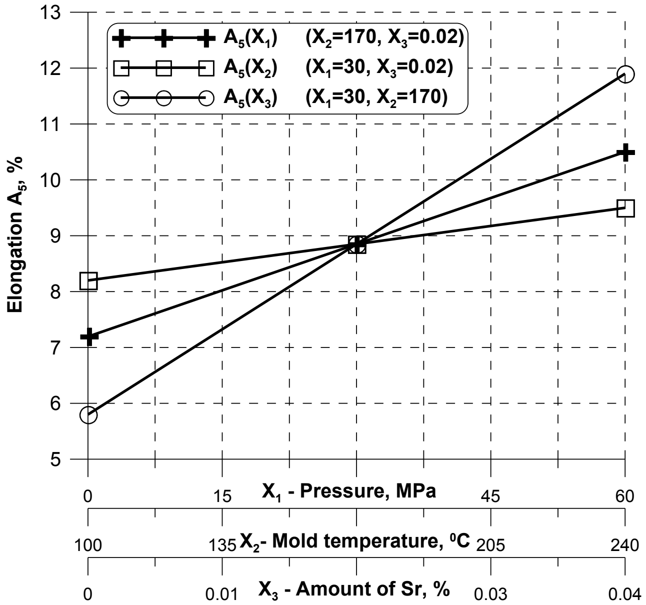

Fig. 2. The influence of squeeze pressure, mould temperature, and quantity of modifier on the elongation A_5 of castings made of AlSi7Mg alloy

The results presented in Table 1 show that the highest strength and plastic properties of casting made of AlSi7Mg alloy are achieved when the values of all indepentent variables reach their high level (experiment N° 1).

4. Final conclusions

1. Application of 2^3 factorial design allowed for determination of the regression equations describing the change of strength and elongation of the AlSi7Mg alloy against the changes in technological parameters of squeeze casting and modification.
2. The mechanical properties of castings made of AlSi7Mg alloy depend, within the examined range of variables, on all three of them, i.e. the squeeze pressure, the quantity of modifier and the mould temperature.
3. The squeeze pressure causes mainly the increase in strength, while modification is the most advantageous way of improving the alloy plasticity.
4. The obtained formulas indicate that the increase in squeeze pressure by 10 MPa results in the increase in R_m by about 10 MPa. The influence of strontium modifier on the elongation manifests itself by the increase of A_5 by 1,5% for each 0.01% of strontium modifier added to the alloy.
5. The change in mould temperature within the examined range of 100-240°C, however statistically significant, does not increase much the mechanical properties of the examined silumin.
6. The modification treatment combined with the squeeze casting technology makes possible the production of AlSi7Mg alloy castings exhibiting the tensile strength at the level of 230 MPa and simultaneously the high unit elongation, exceeding 14%.

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