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Correlations Between Arrangement of Reinforcing Particles and Mechanical Properties in Pressure Die Cast AlSi11-SiC Composites

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Abstract

The work presents the investigation results concerning the structure of composite pressure die castings with AlSi11 alloy matrix reinforced with SiC particles. Examination has been held for composites containing 10 and 20 volume percent of SiC particles. The arrangement of the reinforcing particles within the matrix has been qualitatively assessed in specimens cut out of the castings. The index of distribution was determined on the basis of particle count in elementary measuring fields. The tensile strength, the yield point and elongation of the obtained composite were measured. Composite castings were produced at various values of the piston velocity in the second stage of injection, diverse intensification pressure values, and various injection gate width values. The regression equation describing the change of the considered arrangement particles index and mechanical properties were found as a function of the pressure die casting parameters. The influence of particle arrangement in composite matrix on mechanical properties these material was examined and the functions of correlations between values were obtained. The conclusion gives the analysis and the interpretation of the obtained results.

Keywords: Pressure die casting, Metal matrix composites (MMCs), Aluminium alloy, Structure, Mechanical properties

1. Introduction

Metal matrix composites castings with reinforcing particles are usually produced using multi-stage technologies where one of stages consists in producing stable and uniform composite suspension which after matrix solidification turns finally into a composite. Production of stable and uniform composite suspension depends on a set of surface phenomena occurring at the interface between metal and the non-metallic particle, such as wetting, dipping, adhesion, chemical reactions, and diffusion. They are decisive for the strength of bonding between

components, as well as for the reinforcement arrangement in the composite volume, which in turn provides for achieving the demanded level of composite material properties.

The main problem in achieving the uniform arrangement of nonmetallic particles in the metal matrix is that there occur difficulties in obtaining proper bonding between metal matrix and the particles because the latter are poorly wettable by liquid metal [1,2]. The wettability of components can be improved by surface preparation of particles or by liquid metal modification [3,4]. The non-uniform arrangement of reinforcing particles in the matrix can be caused by sinking down or floating up of the particles

during composite flow. Frequently such a phenomenon occurs during gravity casting of composite suspensions. The arrangement of particles is also influenced by the crystallization process, during which the particles can be engulfed or pushed out by the moving crystallization front what finally results in placing them within interdendritic areas [5,6]. Ceramic particles cause the increase in viscosity of the flowing liquid so the problem of proper filling of the mould or die cavity arise [7,8].

This disadvantageous phenomena can be practically eliminated by employing the pressure die casting method for composite casting production. Then casting parameters can be selected by controlling the injection speed, pressure, and the gate thickness so as to achieve a sound casting containing reinforcing particles uniformly distributed within the matrix [9].

Achieving the high quality of pressure casting depends on the mechanism of filling the die cavity with molten metal [10]. The way of cavity filling is in turn influenced by multiple factors, among which there are the shape and massiveness of a casting, the mass ratio between the casting and the die, the arrangement of the runner and gating system, the shape and the area of the main sprue, the volume of the die cavity, the area and the arrangement of air vents, the injection speed and pressure, and the intensification pressure [11, 12]. Filling of the die and subsequent metal cooling and solidifying strongly depends on such physical properties of cast alloy as its viscosity, solidification range, latent heat of solidification, density, thermal conductivity, and metal temperature, as well as on the die temperature at the moment of pouring [13].

Casting of composites in the semi-solid state is possible only by means of the cold chamber diecasting machines, because high pressure can be applied during pouring operation. The strongly turbulent flow through the gating system results in intensive suspension mixing, what accompanied by quick solidification in the metal die promotes the uniform distribution of reinforcing particles within the volume of matrix.

The properties of composite materials depend on the properties of their components, fractions of individual constituents, their shape, and the bond strength between them, as well as on the technology of final product. Theoretical considerations indicate that the best properties are achieved by metal matrix composites reinforced with continuous fibre. Introduction of particles into the metal matrix creates wide-ranging possibilities of controlling thermal, chemical, electric, and tribological properties.

Two characteristic strengthening mechanisms are distinguished in particulate composites. One of them is the dispersion strengthening mechanism, being realised when small particles, 0.01–1.0 μm in diameter, are introduced and uniformly distributed over the material volume. However, when the size of introduced particles exceeds 1 μm , the character of their interaction with the matrix changes and the strengthening mechanism can be qualified as the particle strengthening.

The mechanism of dispersion strengthening of plastic composite matrix consists in arresting the dislocation movement by means of the particles: the dislocation line is first bent by a particle, then the dislocation loop is formed. This increases the yield point value the more the shorter is the average distance between particles [14].

The composite yield point value decreases parabolically as a function of the average distance between particles, i.e. with the reduction of reinforcing phase fraction. A composite strengthening is achieved when the average distance between particles falls between 0.01 and 0.3 μm , which corresponds to the volume fraction of the particles $V_p = 1\div 20\%$ [15].

The main advantage of dispersion strengthening is not the increased strength at ambient temperature, but the high creeping resistance of the resulting material. Such composites can retain their improved mechanical properties up to the temperature of about 80% of the melting point value [16].

As far as composites containing larger particles are concerned, their ability to bear a load is enhanced not only by arresting of dislocation movement, but also by the occurrence of shearing and slipping inside the particles. However, the yield point value decreases with an increase in particle size.

As far as particulate cast composites are concerned, the properties of castings are influenced most significantly by the type, the size, and the percentage of the reinforcing phase particles, as well as by their distribution within the matrix. The particles of the reinforcing phase can be distributed uniformly or non-uniformly; in this latter case they occupy the intergranular regions in most disadvantageous way. The distribution pattern depends on the quality of the produced suspension, as well as on the casting technology and conditions under which a casting solidifies in the die. The quantitative determination of reinforcing phase distribution within the matrix allows to derive the functional, analytical relationships between the structural parameters and the properties of a casting [17].

2. Material and method of investigation

The commonly used AlSi11 (EN AC-44000) foundry alloy of aluminium and silicon was selected for the composite matrix. Its composition provides for good wettability of particles, thus enabling the introduction of silicon carbide into the matrix without additional treatment or modification of the alloy. The 98C silicon carbide of particle size 71-100 μm was applied in the experiment. The prepared slurries contained 10 and 20 vol.% of the reinforcing phase.

The composite suspension was prepared by mechanical mixing. The laboratory stand at which it was prepared was equipped with the resistance heating furnace with a crucible of about 25 kg capacity, and the turbomixer of 0.25 m diameter with four blades inclined at 45 degrees. The turbomixer rotor was placed axially in the crucible, at a distance of one third of the melt height from the bottom of crucible. The rotor, made of the WNLV steel, was covered with the protective coating which ensured thorough mixing of the whole liquid phase volume and the relatively long lifespan of the mixer itself. The complete mixing system was constructed in such a way that it was possible to close the furnace after adding all components to the crucible. The mixing time was equal to 15 min, and the angular velocity of the rotor was fixed at the level of 500 rpm. The suspension was injected into a test die on the cold chamber horizontal pressure die casting machine of 1.6 MN clamping force.

The examination was performed according to the 2³ type of design of experiment, where the variable factors were: the piston

velocity in the second stage of injection (v_{II}) taking the values of 1.2 or 3.6 m/s, the intensification pressure (p_{III}), being 20 or 40 MPa, and the gate width (d_w) equal to 1.5 or 3 mm. A casting with specimens for castability and impact strength tests, as well as for measuring the mechanical properties was manufactured in one injection cycle [181].

The values of pressure and plunger velocity have been recorded by means of the DMC 200 type sensors made by EMTEC Company. The following constant values have been assumed for the experiments: the diameter of pressing plunger $d_k=40$ mm, the constant plunger velocity in the first stage of injection 0.3 m/s, the degree of the cold chamber filling is 60%, the area of castings with flow-offs and the gating system is 175 cm² in the die parting plane, the suspension temperature (650°C), the die temperature (300°C).

The assessment of the distribution uniformity of the reinforcing phase was done for the non-etched metallographic microsections taken from the tensile specimen shoulders. The examined area was a circle of 10 mm diameter. Panoramic digital images of the whole microsection surfaces were taken at the magnification 50 \times , then the images were merged to achieve an integral image of the entire microsection. A square grid 1 \times 1 mm were superimposed on the area to be measured, dividing it into 79 separate measuring fields. The reinforcing phase particles were counted for each of these unit fields in such a way that the particles crossing the right or the bottom edge of the field were excluded. The observations were performed by means of the OLYMPUS EPIPHOT optical microscope cooperating with a digital image recorder and the MULTISCAN computer data analysis software tool.

Twenty five shots were performed for each machine setting corresponding to the specific point of the design of experiment, so that 100 specimens for static tensile test were produced. Such a large number of castings was necessary in order to achieve and to hold the thermal equilibrium of the die, so that the castings were made under stable and recurrent conditions. The obtained specimens did not require machining.

All mechanical parameters were determined during the tensile test performed according to the PN-EN ISO 6892-1:2010 standard by means of computer controlled Zwick 1488 tensile tester at the following parameters: initial stress equal to 1 MPa, crosshead velocity of 7 mm/min, force capacity – 10 kN. Relevant graphs were recorded during the tensile tests.

The degree of uniformity of distribution of SiC particles within the volume of matrix was found on the basis of the v index, which can be calculated as a ratio of standard deviation of the average quantity of particles over the unit surface area and the average quantity of particles over the unit surface area in mm⁻² [18].

3. Results of investigation

The average measurement results of 5 castings for each experiment concerning the arrangement of particles within the matrix of composite castings and average results of 100 measurements concerning tensile strength, yield point, unit elongation of the examined composite for various casting

parameters are presented in Table 1, while Table 2 shows the values of standard deviations of these measurements.

Taking into account the results shown in Tables 1 and 2, there were derived the regression equations describing the influence of pressure die casting parameters on the v index and mechanical properties of the obtained composite castings.

Table 1.

The values of v index and average values of mechanical properties for individual tests of a given experiment

No. of exp.	v_{II} [m/s]	p_{III} [MPa]	d_w [mm]	v	R_m [MPa]	$R_{0.2}$ [MPa]	A_c [%]
1	2	3	4	5	6	7	8
10.1	1.2	20	1.5	0.62	229.4	213.0	1.44
10.2	1.2	40	3.0	0.37	246.0	196.4	1.41
10.3	1.2	20	3.0	0.87	219.2	183.8	0.98
10.4	1.2	40	1.5	0.29	275.8	226.8	1.64
10.5	3.6	40	3.0	0.27	281.2	224.6	1.57
10.6	3.6	20	1.5	0.25	276.2	225.0	1.63
10.7	3.6	40	1.5	0.19	298.0	235.6	1.91
10.8	3.6	20	3.0	0.28	272.6	218.6	1.45
20.1	1.2	20	1.5	0.28	212.0	185.8	0.29
20.2	1.2	40	3.0	0.47	220.6	184.8	0.20
20.3	1.2	20	3.0	0.65	188.6	189.2	0.14
20.4	1.2	40	1.5	0.26	231.6	216.8	0.37
20.5	3.6	40	3.0	0.18	256.2	223.8	0.25
20.6	3.6	20	1.5	0.20	262.8	217.8	0.41
20.7	3.6	40	1.5	0.15	269.6	225.2	0.47
20.8	3.6	20	3.0	0.23	252.4	211.6	0.24

Table 2.

Standard deviations of the measured values of the examined composite

No. of exp.	v_{II} , m/s	p_{III} , MPa	d_w , mm	S_v	S_{Rm} MPa	$S_{R0.2}$ MPa	S_{Ac} %
1	2	3	4	5	6	7	8
10.1	1.2	20	1.5	0.032	7,7	11,0	0,131
10.2	1.2	40	3.0	0.028	9,0	9,6	0,174
10.3	1.2	20	3.0	0.045	13,8	12,2	0,085
10.4	1.2	40	1.5	0.021	10,1	8,8	0,252
10.5	3.6	40	3.0	0.020	9,5	10,6	0,173
10.6	3.6	20	1.5	0.022	7,4	6,0	0,231
10.7	3.6	40	1.5	0.016	5,9	6,6	0,112
10.8	3.6	20	3.0	0.023	8,8	9,9	0,160
20.1	1.2	20	1.5	0.028	5,6	6,1	0,089
20.2	1.2	40	3.0	0.034	8,2	6,9	0,093
20.3	1.2	20	3.0	0.047	6,6	5,0	0,122
20.4	1.2	40	1.5	0.026	5,0	5,5	0,107
20.5	3.6	40	3.0	0.017	7,3	7,0	0,096
20.6	3.6	20	1.5	0.017	4,9	5,8	0,091
20.7	3.6	40	1.5	0.012	6,5	6,1	0,110
20.8	3.6	20	3.0	0.029	7,7	6,8	0,086

These equations take the following form for coded independent variables ($x_1 = v_{II}$, $x_2 = p_{III}$ and $x_3 = d_w$). To calculate the chosen casting properties the +1, 0 or -1 should be put as a values of independent variables in suitable equation.

$$v_{10} = 0,39 - 0,14x_1 - 0,11x_2 + 0,06x_3 + 0,09x_1x_2 \quad (1)$$

$$v_{20} = 0,30 - 0,11x_1 - 0,04x_2 + 0,08x_3 - 0,06x_1x_3 - 0,02x_2x_3 \quad (2)$$

$$R_{m10} = 262,3 + 19,7x_1 + 12,9x_2 - 7,5x_3 \quad (3)$$

$$R_{m20} = 236,7 + 23,5x_1 + 7,8x_2 - 7,3x_3 \quad (4)$$

$$R_{02,10} = 215,5 + 10,5x_1 + 5,4x_2 - 9,6x_3 - 5,3x_1x_3 \quad (5)$$

$$R_{02,20} = 206,9 + 12,7x_1 + 5,8x_2 - 4,5x_3 \quad (6)$$

$$A_{5,10} = 1,50 + 0,14x_1 + 0,13x_2 - 0,15x_3 \quad (7)$$

$$A_{5,20} = 0,30 + 0,04x_1 + 0,03x_2 - 0,09x_3 \quad (8)$$

Significant non-linear effects of casting parameters on arrangement of SiC particles in composite matrix were observed (eq. 1 and 2). The plunger velocity during second stage of pressure die casting have stronger effect on composite structure and mechanical properties in composites containing 20% SiC particles.

The linear approximation of correlation between arrangement of reinforcing particles SiC in matrix composites calculated by means of the v index and mechanical properties of examined composites were shown in Figs 1-3.

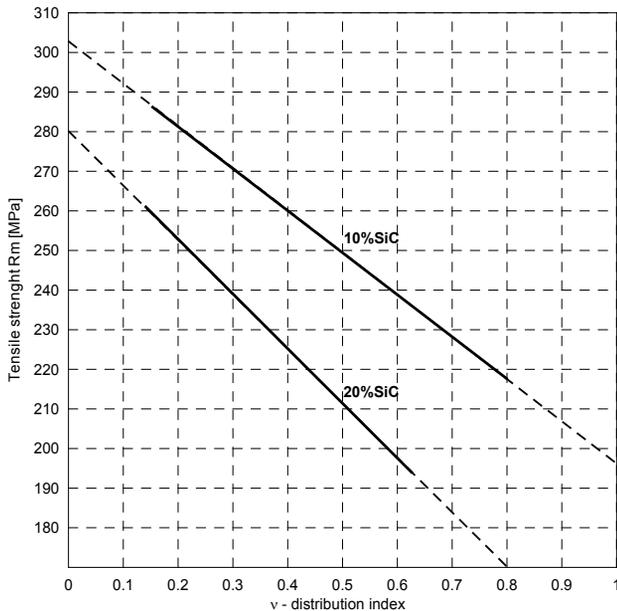


Fig. 1. Linear approximation of correlation v and R_m for AlSi11-10%SiC i AlSi11-20%SiC composites.

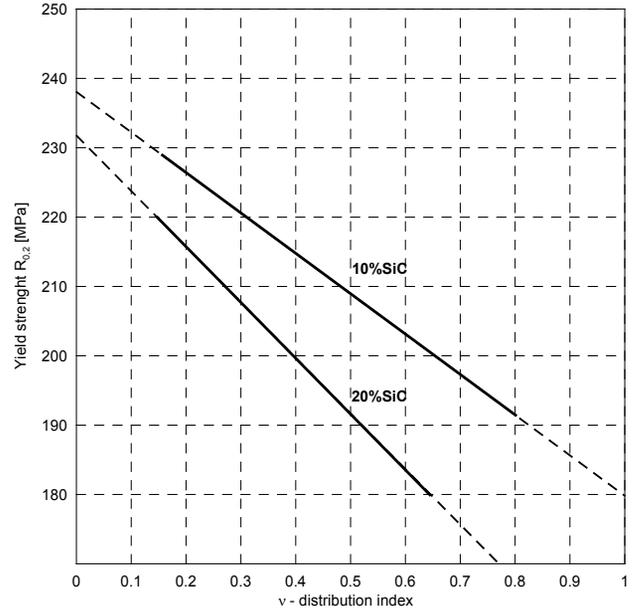


Fig. 2. Linear approximation of correlation v and R_{02} for AlSi11-10%SiC i AlSi11-20%SiC composites.

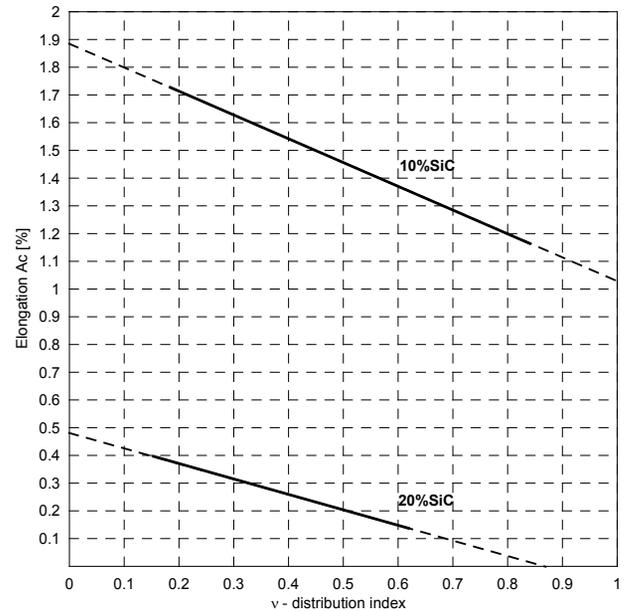


Fig. 3. Linear approximation of correlation v and A_5 for AlSi11-10%SiC i AlSi11-20%SiC composites.

4. Conclusions

It was noticed that the low values of parameters support the non-uniform distribution or even generation of particle clusters in the composite suspension (eq.1 and 2).

A strong influence of the piston velocity in the second stage of injection on the distribution of particles within the metal matrix is observed. An increase in each of these parameters results in the increase in the uniformity of distribution of the SiC particles in the matrix. The influence of gate width is of minor significance for the improvement of the uniformity of reinforcing phase distribution. The obtained results point out unequivocally to the optimum parameters of pressure die casting for composites of this type.

An increased piston velocity combined with the reduced gate width also improved the uniformity of the reinforcing phase distribution. This increase results from the fact of intensive mixing of the suspension in the gate and the rapid filling of the die with the prepared suspension. The intensification pressure occurred to exert less significant influence on the uniformity of distribution of the particles at the large values of injection velocity, however – as far as the castings containing 10% of reinforcement are concerned – the uniformity achieved at high intensification pressure and low injection velocity was better than the one achieved for low intensification pressure and low injection speed.

The combined influence of piston velocity at the stage of die filling and of the gate width (or its cross-sectional area) can be expressed by the rate of the die filling (the injection rate). This rate changed from 16 m/s to 96 m/s in the course of examinations.

It results clearly from the derived equations that the piston velocity in the second stage of injection influences most significantly the mechanical properties of composite castings. An increase in the piston velocity during the mould filling and the reduction of gate area (i.e. thinner gate) result in the increase in cavity filling rate. The increased injection rate is accompanied by the increased tensile strength of composite castings, and the largest increase corresponds to the injection speed of 50 m/s.

High filling rates provide for intensive mixing of the slurry at the gate, thus promoting the uniform distribution of reinforcing phase particles and improving the mechanical properties of castings. However, attention should be paid to the significance of intensification pressure for the improvement of mechanical properties of castings. The castings produced under the increased intensification pressure were characterised by higher strength than those which solidified under lower pressure. It is characteristic for the improvement that the high intensification pressure increased the density of castings by partial elimination or compressing the unavoidable gas occlusions, thus enlarging the adhesion area at the metal/particle interface. The metal injected under high pressure and then subjected to intensification pressure adheres tightly to the particle, filling its pores and enfolding its projections, by the same contributing to the better test results exhibited by specimens cast under the increased intensification pressure.

In the case of yield strength the most significant parameters occurred to be the piston velocity in the second stage of injection and the gate width. The presence of reinforcing phase lowers such characteristics as yield strength and unit elongation, and casting

parameters only slightly influence their values. The increased quantity of particles in the volume of a casting results in the reduced unit elongation.

The AlSi11 alloy used for the purpose of experiment exhibits unit elongation of about 3%. After the introduction of reinforcing particles, however, the elongation was reduced by half as an average in composites with 10% SiC and significant lower in composites with 20% SiC

The value of unit elongation was influenced, similarly as R_m or $R_{0.2}$, by the applied pressure die casting parameters. Comparable absolute values of regression coefficients indicate the equivalent power of affecting the results exhibited by all three considered parameters. Still, the most significant occurred to be the gate width, then the piston velocity, and only then the intensification pressure. Due to the presence of brittle ceramic particles the composite almost does not deform plastically, but brittle cracks along the weak adhesive bonding between metal and ceramics.

The examinations allow to draw the following conclusions:

- application of the pressure die casting technology for production of the AlSi11/SiC composite castings allow to modify the character of distribution of ceramic particles in metal matrix within a wide range;
- parameters of the production process, i.e. the piston velocity in the second stage of injection, the intensification pressure and the gate width, exert the essential influence on the type of composite structure with respect to the distribution of the reinforcing phase particles; this distribution can be uniform, non-uniform, or non-uniform with clusters;
- the increase in injection rate due to the increase in piston velocity in the second stage of injection and the reduction of gate area strongly promote the uniform distribution of reinforcing particles within the volume of castings.
- It results from the above diagram that for injection rates exceeding 50 m/s there is no significant improvement in the distribution of the reinforcing phase particles in the matrix of composite castings. (181)
- main parameters of production process, i.e. the piston velocity in the second stage of injection, the intensification pressure, and the gate width, exert fundamental influence on mechanical properties of composite castings;
- the measured values of mechanical properties of the examined composite are characterised by great uniformity, thus confirming the optimum proceeding of the slurry preparation and of the high-pressure die casting process. (184)

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