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INVESTIGATION OF PRESSURE DIE CASTING OF THE ALUMINIUM ALLOY MATRIX COMPOSITES WITH SiC PARTICLES

BADANIE ODLEWANIA CIŚNIENIOWEGO KOMPOZYTÓW NA OSNOWIE STOPU Al Z CZĄSTKAMI SiC

The purpose of the work is determining the optimum values of both the plunger velocity during the second stage of injection and the intensification pressure applied in pressure die casting technology for aluminium alloy matrix composites with SiC particles uniformly distributed in the volume of metal. The pressure die casting of composite consisting of EN AC – 44000 alloy matrix reinforced with 10 or 20 vol. % of silicon carbide particles has been investigated. Production of composite suspensions composed of the molten aluminium alloy and the solid SiC particles has been described. Casting has been performed according to the factor design of experiment using the cold-chamber horizontal pressure die casting machine at various intensification pressure values, equal to 10 or 20 MPa, and various plunger velocity values during the second phase of injection, equal to 1.2 or 3.5 m/s. There have been cast tensile specimens of average wall thickness assumed equal to 7 mm. The density of the pressure composite castings has been assumed as the quality indicator. The obtained density results for the examined composites have allowed for determining the average porosity of the castings, which reflects both the filling mechanism and air escape from the die cavity. Regression equations of the influence of casting parameters on density and porosity of pressure composite castings have been derived. The statistical analysis has allowed for stating that the increase in density for composites containing 10% of SiC is advantageously influenced by the plunger velocity, while the influence of pressure has occurred to be negligible. On the contrary, the intensification pressure is significant for pressure die casting of composite containing 20% of SiC particles. In turn, the results of porosity calculation have shown that the least porosity of composite reinforced with 10% of SiC has been obtained for the largest values of the intensification pressure, and the plunger velocity in the second phase has been of no significance. The porosity of composite castings with 20% of particles decrease in a linear manner with an increase of the plunger speed and intensification pressure. Observations of composite structure have revealed the uniform distribution of the particles in the matrix, what confirms the high effectiveness both of the suspension production by the mechanical mixing method and of its pressure die casting.

Celem pracy jest ustalenie optymalnych wartości prędkości tłoka w II fazie i ciśnienia doprasowania dla technologii odlewania ciśnieniowego kompozytów na osnowie stopów aluminium z równomiernie rozmieszczonymi w całej objętości cząstkami SiC. Badano ciśnieniowe odlewanie kompozytu na osnowie stopu EN AC – 44000 umocnionego 10 i 20% udziałem objętościowym cząstek węglika krzemu. Przedstawiono opis wytwarzania zawiesin kompozytowych ciekły stop aluminium-cząstki stałe SiC. Odlewanie realizowano według czynnikowego planu doświadczeń na zimnokomorowej poziomej maszynie ciśnieniowej przy zmiennym ciśnieniu doprasowania wynoszącym 10 i 20 MPa oraz prędkości tłoka w drugiej fazie równej 1.2 i 3.5 m/s. Wykonano odlewy próbek wytrzymałościowych, dla których przyjęto średnią grubość ścianki 7 mm. Mierzono gęstość ciśnieniowych odlewów kompozytowych, którą przyjęto jako wskaźnik jakości. Otrzymane wyniki gęstości dla badanych kompozytów umożliwiły określenie średniej porowatości odlewów, która odzwierciedla mechanizm wypełniania i ewakuację powietrza z wnęki formy. Wyznaczono równania regresji wpływu parametrów odlewania na gęstość i porowatość ciśnieniowych odlewów kompozytowych. Na podstawie analizy statystycznej stwierdzono, że na wzrost gęstości kompozytów z 10% udziałem SiC dodatni wpływ wywiera prędkość tłoka, a wpływ ciśnienia okazał się nieistotny. Natomiast dla kompozytu z 20% SiC znaczące przy odlewaniu ciśnieniowym jest zwiększenie ciśnienia doprasowania. Z kolei wyniki obliczeń porowatości wykazały, że najmniejszą porowatość kompozytu umocnionego 10% SiC otrzymano przy największych wartościach ciśnienia doprasowania, przy nieistotnym wpływie prędkości tłoka w II fazie. Porowatość odlewów kompozytowych z 20% udziałem cząstek SiC liniowo spada ze wzrostem prędkości tłoka i ciśnienia doprasowania. Obserwacje struktury kompozytów wykazały równomierne rozmieszczenie cząstek w osnowie, co potwierdza wysoką efektywność wytwarzania zawiesiny metodą mieszania mechanicznego i jej odlewania ciśnieniowego.

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1. Introduction

Production of aluminium alloy matrix composites containing ceramic particles depends on many factors concerned, on the one hand, in the process of suspension making and in the casting technology on the other [1, 6, 8]. Most of known methods of producing the suspension of aluminium alloy and ceramic particles use mechanical mixing with simultaneous introducing the particles into the molten metal [2, 3]. Suspension production is possible thanks to the good wettability of particles with the molten metal and the occurring of radial-axial circulation of liquid metal in the stirring vessel [4, 5]. Application of both optimum angular velocity of the stirrer and the proper mixing time provides for obtaining the uniform suspension. Composite suspension exhibits greater viscosity and lower castability as compared with liquid aluminium alloy, what distinctly changes the die filling conditions. Many factors influence the die cavity filling, among them viscosity, surface tension, gas and oxide content, thermal and physical properties of the die, as well as the system temperature [11, 12, 13]. The presence of solid particles affects the composite crystallization process by their contribution both to the nucleation process and to the crystallization front movement, thus hindering the die filling at the assumption of low cooling rate. Ceramic particles can float up or sink down during flow due to the difference between specific weight of the particles and the matrix, what leads to segregation and by the same to the deterioration of casting properties [7, 8]. These disadvantageous phenomena does not occur if the cooling and solidification rates are high. One of the basic conditions of obtaining the composite of good quality is uniform distribution of the reinforcement in the whole volume of matrix [8, 9]. Aluminium alloys reinforced with silicon carbide particles form composite systems of high strength and tribological properties, what puts them among modern materials of special properties [6, 10]. Due to the high viscosity of composite suspension and difficult conditions of die filling, the preferred method of their casting are those which use the forced die filling. Here pressure die casting should be mentioned as the possibly most useful method [14, 15]. The high pressure die casting of particulate composite materials fulfils requirements of forced die cavity filling and quick cooling and solidifying of a casting.

Pressure casting causes intensive mixing of composite suspension due to the high velocity of metal in the runner and the die cavity, thus promoting the uniform distribution of the reinforcing phase within the composite matrix [16, 17, 18]. The process of filling the die cavity with liquid metal depends on the type of applied pressing unit and casting parameters and is decisive for the quality of castings. Thanks to the high filling rate this technology allows for achieving the thin-walled and greatly complicated objects of a quite good dimensional accuracy. The fine grain structure of pressure castings improve their mechanical properties as compared with those of sand cast items [20, 21]. Applying of composite pressure die casting allows also for taking advantage of a characteristic property of 'rheocast' structure arising within composite suspension as a result of partial solidification of the alloy after introducing the particles. Composite suspension casting can be then considered as a type of thixsotropic casting. Additionally, the high smoothness of the surface of such castings often eliminates machining and surface cleaning, what is of special importance in the case of composites, usually containing hard and non-machinable reinforcing particles [19, 22].

2. Methodics and the results of investigations

The experiments have been carried out for composite material with EN AC-44000 aluminium alloy matrix (according to PN – EN 1706 Standard) of the following chemical composition 10–11.8% Si, 0.19% Fe, 0.05% Cu, 0.1% Mn, 0.45% Mg, 0.07% Zn, 0.15% Ti. This alloy has been reinforced with 10 or 20 volume percent of SiC particles of 100 μm size. Composites have been produced by mechanical mixing of the liquid matrix with a stirrer and simultaneous introducing the powdered reinforcing phase at the temperature of 950 K, the angular velocity of the stirrer equal to 0.5 s^{-1}, and the mixing time of 10 min. The obtained suspension has been pressure cast from the 923 K temperature using the horizontal cold chamber die casting machine with the clamping force equal to 200 MN. Composites have been cast into the experimental die, receiving tensile specimens with the average wall thickness of 7 mm. The specimens have been examined by means of the optical microscope to assess their structure and distribution of the particles in the matrix.

The examinations have dealt with the influence of two variable parameters of pressure casting process on density and porosity of the obtained composite. It has been assumed that the die cavity filling will proceed at various values of the plunger velocity in the second phase of injection, namely 1.2 or 3.5 m/s, and the various values of the intensification pressure in the third stage of the process, which have been assumed as 10 or 20 MPa. Experiments have been carried out according to the factor design of extreme experiment of the 2^2 type [23, 24]. For each experiment 5 die cavity fillings have been performed, what gives a total of 20 castings to be examined. The investigated values have been recorded versus time during the casting process. The injection parameters have been measured with DMC 200 system sensors made by EMTEC. The density measurements have been carried out by weighing. The obtained density results have allowed also for determining the average porosity for the investigated composites containing both 10 and 20 percent of SiC particles. The porosity value has been calculated on the basis of the theoretical density value derived from the mixing rule for given composites and the actual density obtained from the measurements, as a ratio of the difference between theoretical and actual density and theoretical density [20, 21]. The theoretical density for EN AC–44000 alloy containing 10% of SiC equals to 2705 kg/m^3 and for the same alloy containing 20% of SiC it increases to 2760 kg/m^3.

The obtained results have been statistically analysed and the regression equations describing the investigated factor domain have been derived [24, 25]. The regression equations, being mathematical models describing the influence of the plunger velocity and the intensification pressure on the density of composite castings, are the result of the initial stage of pressure die casting optimisation for composite materials. The experimental design matrix along with the average density and porosity values calculated from five composite samples each, as well as the calculated variances of results for given experiments are presented in Table.

TABLE

The design matrix along with density ρ and porosity K values

	v [m/s]	p [MPa]	ρ kg/m^3	S^2_ρ	K, %	S^2_K
EN AC-44000 + 10% SiC	1.2	10	2652	192	1.95	2.63
	1.2	20	2655	20	1.84	0.27
	3.5	10	2673	15	1.18	0.04
	3.5	20	2685	143	0.73	0.17
EN AC-44000 + 20% SiC	1.2	10	2652	192	1.95	2.63
	1.2	20	2655	20	1.84	0.27
	3.5	10	2673	15	1.18	0.04
	3.5	20	2685	143	0.73	0.17

The regression equation for the investigated domain have been received from the statistic analysis of the results. For the EN AC-44000 alloy/10% SiC composite density ρ_{10} the following regression equation has been derived:

$$\rho_{10} = 2640.2 + 11.09\ v, \qquad (1)$$

where v is the plunger velocity in m/s.

In turn, for the EN AC-44000 alloy/20% SiC composite density ρ_{20} the regression equation takes the form:

$$\rho_{20} = 2489.21 - 14.17\ p + 65.87\ v - 4.39\ v\ p, \qquad (2)$$

where p is the intensification pressure in MPa.

The executed statistic analysis has revealed that during the pressure die casting of the composites reinforced with 10% of SiC volume fraction the intensification pressure has a non-significant influence for obtaining the optimum density of the composite, while the plunger velocity is here a significant parameter. On the contrary, for the EN AC-44000 alloy + 20% SiC composite, where the reinforcing phase fraction is much greater, the significant parameters for obtaining the best density of the composite are the plunger velocity and the intensification pressure.

The analysis of experimental results has shown that for the samples cast of the composite with 10% fraction of reinforcement the lowest porosity has been achieved at the greatest values of the intensification pressure and the greatest plunger velocity. This porosity has been 0.7% and it has been twice less than the porosity of composite cast at a different set of parameters. However, for the increased fraction of SiC particles the most advantageous porosity, nearly one fourth of the value obtained for other 20% SiC composite specimens, has been achieved at the largest intensification pressure, but the lowest plunger velocity in the second stage of injection.

Two regression equations for the examined domain has been formulated on the basis of the statistic analysis of the significant results of porosity examination. For the EN AC-44000 alloy reinforced with 10% of SiC particles the following regression equation using uncoded variables has been found:

$$K_{10} = 2.38 - 0.41\ v. \qquad (3)$$

In turn, the regression equation for the EN AC-44000 alloy/20% SiC composite porosity K_{20} occurred to be dependent on both intensification pressure and the plunger velocity in the second stage of injection:

$$K_{20} = 9.80 - 0.51\ p - 2.40\ v + 0.16\ v\ p. \qquad (4)$$

Graphic interpretation of the obtained mathematical models for density (Formulae 1, 2) and porosity (Formulae 3, 4) for the EN AC-44000 alloy + 10% or 20% SiC composites is presented in Figures 1 and 2, respectively.

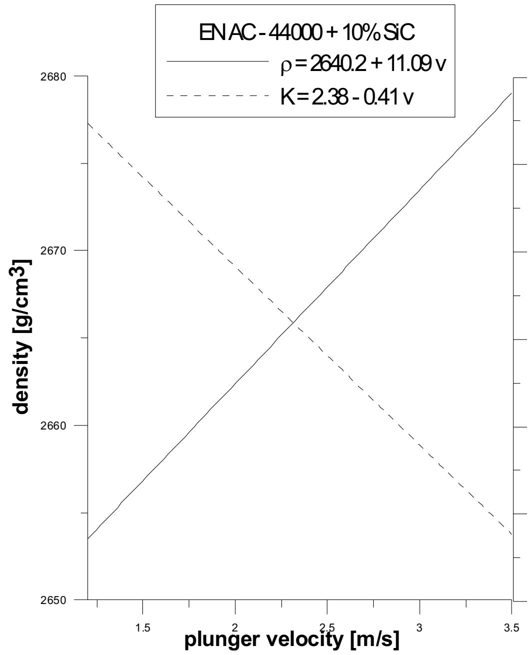

Fig. 1. Change of density and porosity of the EN AC-44000 alloy + 10% SiC particles composite

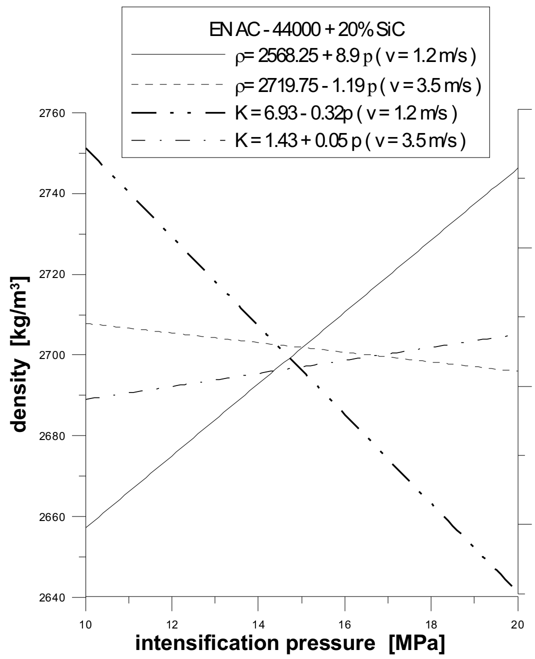

Fig. 2. Change of density and porosity of the EN AC-44000 alloy + 20% SiC particles composite

Microstructural examination of the investigated composites has confirmed the almost uniform distribution of silicon carbide particles in the whole volume of matrix. Figures 3 and 4 present the photographs of microstructures of the EN AC-44000 alloy + 10% or 20% SiC composites at 25× magnification.

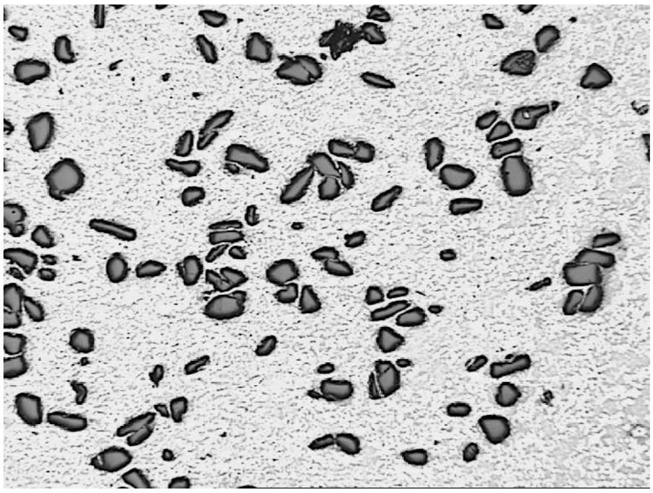

Fig. 3. Microstructure of the EN AC-44000 alloy + 10% SiC composite (magn. 25×)

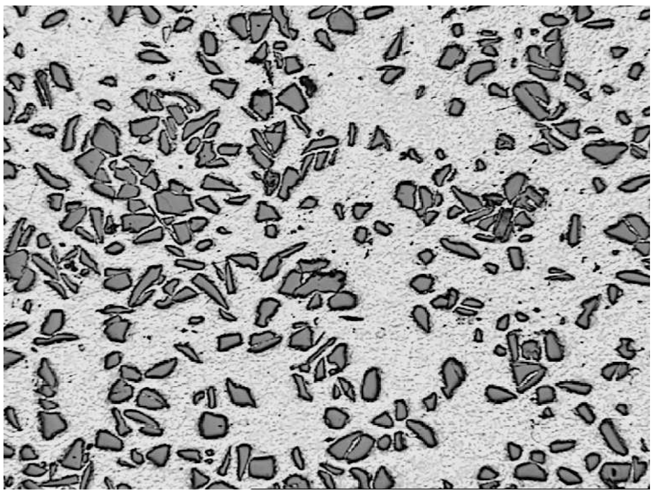

Fig. 4. Microstructure of the EN AC-44000 alloy + 20% SiC composite (magn. 25×)

3. Conclusion

The applied technology of mixing and pressure casting has allowed for production of composites characterised with uniformly distribution of particles in the whole volume of matrix and low porosity. Realisation of research work according to the assumed design of experiment has enabled derivation of equations describing the influence of pressure die casting parameters on composite density and porosity.

The performed statistic analysis of the composite density results, as related to the two investigated parameters of pressure casting, gives a basis for stating that during the EN AC-4000 alloy + 10% SiC composite casting, when metal suspension viscosity is relatively not so large, increasing of the plunger velocity in the second stage of injection facilitates the die cavity filling.

Thanks to the high speed of metal in the runner and in the die, the intensive mixing of suspension composite occurs thus enabling the achievement of the reinforcement uniform distribution within the volume of matrix. The influence of the intensification pressure on the composite density is not observed due to the quick cooling of metal.

Casting of the composite of the increased viscosity i.e. the one being reinforced with 20% fraction of SiC particles proceeds in turn under the conditions of hindered suspension flow. Increasing of the plunger velocity is effective despite the significant resistance to flow. In this case the influence of intensification pressure is exposed because the die filling proceeds in the form of suspension squeezing. This problem requires taking into account the influence of the lap gate width on the die cavity filling. Squeezing of the liquid-solid suspension into the die cavity is improved with the intensification pressure increase.

The obtained porosity results for composite containing 10% of SiC particles confirm the contribution of the plunger velocity to the decrease of porosity, while there is no influence of intensification pressure (Eq. 3). At the plunger velocity of 3.5 m/s the porosity of castings is twice less as compared with the castings made at the plunger velocity of 1.2 m/s. Such a results is correlated with the density changes for this composite (Eq. 2). Composites containing 20% of SiC particles exhibit different relationships between casting parameters and the changes of density and porosity. In this case porosity of the composite castings depends strongly of both plunger velocity and the intensification pressure. The increase of these parameters results in a linear drop of the porosity of castings with a slight non-linear interaction. This qualitative difference between porosity and density changes of porosity and can be however attributed to the assumed definition of porosity and its calculation on the basis of the density results, and not to the change of the influence of casting parameters for this particular composite.

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