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Attempts to Prepare Precision Composite Castings by Sintering Al_2O_3/AlSi11 Using Underpressure

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Abstract

This article presents the preparation of composite casts made using the technology of precise casting by the method of melted models. The composite was reinforced with the ceramic sinter from Al_2O_3 particle shaped in a printed polystyrene female mould, which was fired together with precured ceramics. The resulting ceramic preform, after being saturated with paraffin and after the filling system is installed, was filled with liquid moulding sand and fired together with the mould. The reinforcement was saturated by means of the counter-pressure exerting action on the metal column, being a resultant of pressures inside and outside the chamber. The preliminary assessment showed no apparent defects in the shape of the cast. The casting was measured and the figures were compared with the dimensions of the matrix in which the reinforcing preform was made, the preform after firing and after saturation with paraffin. The results were presented in a table and dimensional deviations were determined. The composite casting was subjected to metallographic tests, which excluded any porous defects or damage to the reinforcement. It can therefore be said that, according to the predictions resulting from the previous calculations, the pressure values used allowed for complete filling of the reinforcement capillaries. The proposed method is therefore suitable for the preparation of precision composite castings with complex shapes.

Keywords: Innovative foundry technologies and materials, Composites, Rapid prototyping

1. Introduction

A significant group of metal composites are composites made of aluminium alloy matrix, reinforced with ceramics [1-6]. The ceramic reinforcement may be in the form of particles or 3D skeleton structures. In the case of composites reinforced with particles, mainly carbides or oxides are used, which form a suspension after being introduced into the alloy. The prepared suspension is shaped by conventional foundry methods, as in most cases the composite suspension has castability similar to that of standard foundry alloys [7].

In the case of 3D skeleton structures, the reinforcement is often produced by bonding short, disordered ceramic fibres or by sintering particles [2, 6]. The porous reinforcing preforms prepared in this way are then saturated, in the pressurised state, with liquid alloy to form a composite. Poor wettability of ceramics with liquid aluminium alloys and the gas pressure in capillaries of the reinforcing preform necessitate the exertion of very high pressures on the metal column. The pressure on the metal can be generated by different methods, by applying pressure with a stamp or exerting a centrifugal force [8-12]. The prerequisite for preparation of a composite in this way is the introduction, at a pressure higher than the capillary pressure, of the metal mould of the liquid alloy, placed in a socket, into the previously-made ceramic preform [2-3, 5]. Saturation carried out in this way can be refined by improving the wettability of ceramics by applying various types of metal coatings to their surface, but these are complex and time-consuming treatments, and therefore often expensive [2, 6, 8]. However, the most important problem when saturating the preform with liquid metal is the atmospheric air present in the reinforcement capillaries. During the saturation, the capillaries' air pressure increases proportionally to the pressure acting on the metal, making it impossible to fill the moulded part completely, which results in the formation of porosity defects and lowering the quality of the material [2, 7, 11-19]. Therefore, the fundamental phenomenon to be analysed is the pressure changes in the composite casting during the solidification of its metal matrix. Ideally, the solidification can be carried out at a pressure equal to or even greater than the saturation pressure [7, 13-15]. In real-life conditions, however, pressure may become reduced locally due to:

1) the solidification of the casting considered macroscopically,
2) isolation of micro-areas on the front of crystallization.

The first case is depicted in Figure 1.

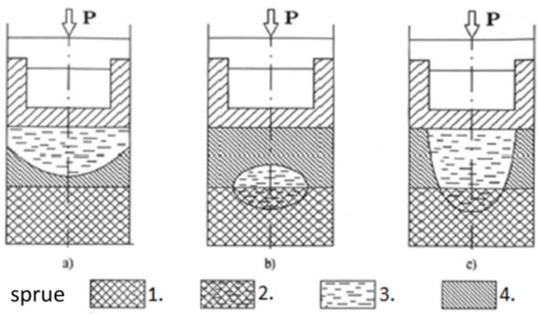

Fig. 1. Solidification of the matrix metal in the casting area: a – non-isolated, b – fully isolated, c – partially isolated, 1. Left to right: reinforcement with solidified metal; 2. Reinforcement with liquid metal; 3. Liquid metal; 4. Solidified metal [14]

In case (a) (Fig. 1) the crystallization front moving towards the sprue. This guarantees the solidification of almost the entire casting volume under a pressure equal to the external pressure. In cases (b) and (c) (Fig. 1), the pressure of the pressing stamp is absorbed partially or completely by the solidified part of the matrix metal. This results in complete or partial isolation of the liquid metal. As a result of this isolation of the metal, which can only exceptionally be treated as an incompressible liquid, the pressure in this metal is reduced. The reduction depends on:

– the ratio of the stamp's pressure force to its part absorbed by the solidified metal;
– quantities of gases, occluded or dissolved in the metal, the expansion or precipitation of which makes the liquid metal act as a compressible liquid.

The expansion of gases occluded in isolated areas leads to an increase in the volume of gases contained in pores. As a result, the occluded pores are characterised by a variable volume. They are smallest in non-isolated zones, increasing in size over the paths leading to isolated zones. An example of blisters enclosed (occluded) in a composite is shown in Figure 2 and porosity composites in Figure 3a.

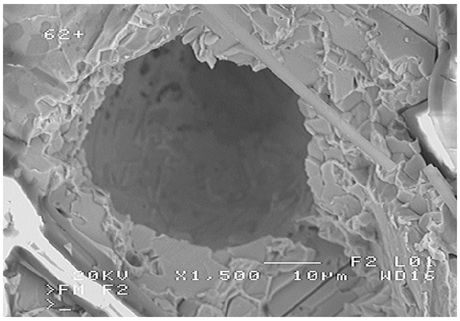

Fig. 2. Gaseous occlusion; composite – reinforcement: aluminosilicate, matrix – Wood alloy; (SEM, surface as shown in the drawings).

Isolation of microareas at the crystallization front, being the second reason for local pressure decrease in the solidifying metal, is related to the nature of the crystallization front. The type of crystallisation depends on the type of alloy and the temperature gradient in the areas of the crystallisation front. A high thermal gradient and a narrow range between the liquidus and solidus temperatures are conducive to the formation of a layered crystallization front, while a low gradient and a wide range between liquidus and solidus temperatures are conducive to the formation of an abundant crystallization front. In extreme cases, a pressure higher than necessary to fill the capillaries is undesirable as it can lead to deformation or displacement of the reinforcing preform [15]. It also introduces excessive stresses in the preform in the areas of the liquid metal front, which can lead to cracks, breaks and gaps in the reinforcing structure. This disadvantage is illustrated in Figure 3.

Methods are known to eliminate this problem, such as saturation in the autoclave, which consists in immersing the ceramic preform in the liquid metal, where a vacuum is created in the first stage of the process to remove air from the capillaries, and then the pressure in the chamber is equalized, causing the capillaries to be filled with liquid alloy [2, 6, 8, 11, 15-24]. These methods, although effective, do not fit in with foundry technologies, where, by definition, the shape of the casting is given by the mould. Besides, often after removing the saturated casting from the liquid metal, the capillary parts are emptied spontaneously, which causes incomplete saturation of the reinforcement. The authors aimed to find a method of producing a precise composite casting with saturated reinforcement with satisfactory properties [9-13]. Precision casting (obtaining the final shape of the casting) does not require processing, which in the case of composites with ceramic reinforcements would have to involve the use of special cutting tools or laser support [25-27]. This applies both to composites reinforced with SiC particles and ceramic sinters.

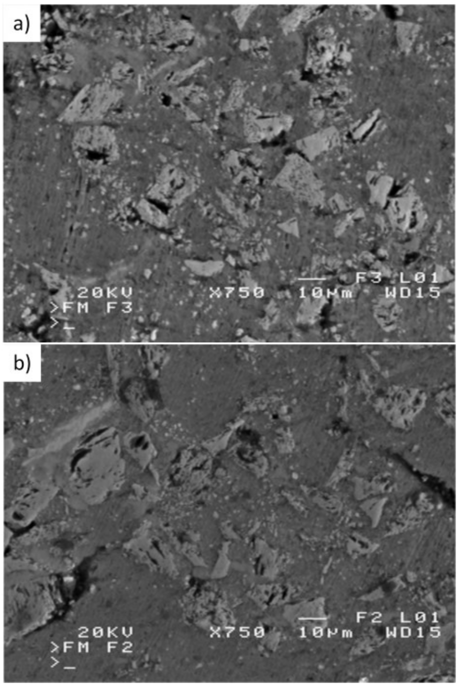

Fig. 3. Porosity composites a – reinforcement: SiC particles, matrix: AlSi12, sintered ceramic and cracks in the reinforcing of minor particles; b – reinforcement SiC particles, matrix: AlSi9, sintered ceramic (SEM, surface as shown in the drawings)

2. Experimental procedure

The first stage of the research involved making a ceramic preform reflecting the future shape of the casting. The ceramic preform was prepared by sintering aluminium oxide powder – Al_2O_3. The basic physical characteristics of the material used in this process are shown in Table 1. The sinter was made of Al_2O_3 particles with a size of 100-150 µm, marked as 100 in the FEPA scale. The porosity used reinforcement was around 47%.

To facilitate the preparation of the reinforcing preform, about 10% of water glass has been added to the powder of Al_2O_3 and mixed well. The ceramic mass prepared in this way was poured into a 3D-printed female mould (Fig. 4) and slightly thickened.

Fig. 4. The female mould for the ceramic preform

In order to pre-bind the components, the resulting preform was blown through with CO_2 and then fired in the furnace in order to completely bind the material and remove the matrix. The 22-hours annealing cycle occurred in two stages. The maximum temperature of 1500°C applied in this cycle caused the partial melting of ceramic particles and water glass. After annealing, the preform was placed in the female mould again and saturated with paraffin. The saturation was intended to protect the preform against penetration of the liquid moulding sand. The wax gate assembly (Fig. 5) was soldered to the paraffin-impregnated preform and the whole part was placed in a perforated stainless steel sleeve with the following dimensions: diameter – 75 mm, height – 120 mm.

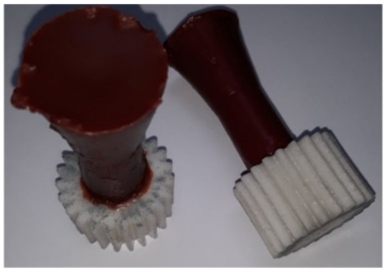

Fig. 5. The reinforcing preform with gate assembly attached

Then the sleeve was filled with the casting gypsum mass. After setting and drying, the mould (Fig. 6) was placed in an oven, where the gating system was melted down in the first cycle and then the mould was annealed in the incremental cycle until it reached the temperature of 720°C. During this time, the paraffin in the capillaries of the reinforcing preform was completely gasified and the mould was completely set. The entire mould preparation process consists of following stages: preparation of the female mould, preparation of the mass made of Al_2O_3 /sodium silicate, filling with the Al_2O_3 mass and curing with CO_2,

Table 1.
Selected physical properties of aluminium oxide

Material	Density, [kg/m^3]	Melting point, [K]	Specific heat [kJ/(kg·K)]	Coefficient of thermal conductivity, [W/(m·K)].	Microhardness, [GPa]	Thermal expansion coefficient α, [106, 1/K]
Al_2O_3	3970	2288	1.09	30.2	10–12	6.5–8.0

annealing of the preform, preform impregnation with paraffin, soldering the gating system in order to attach it, filling the model system with the ceramic mass, melting down the gating system and annealing the mould.

Fig. 6. The mould prepared for firing

The infiltration process took place on the bench shown in Figure 7. The mould was filled with a standard near-eutectic aluminium alloy AlSi12(b) of temperature 750°C. The temperature of mould and reinforcement was 620°C. The minimum pressure in the saturation chamber was 5000 Pa, capillary pressure 50000 Pa, metallostatic pressure 1380 Pa. The procedure was as follows:

– place the mould on the bench,
– start the vacuum pump,
– fill the mould with liquid alloy,
– stop the pump after the alloy solidifies.

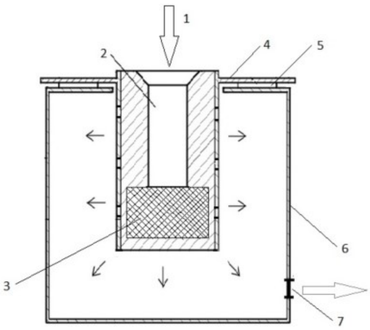

Fig. 7. The diagram of the mould filling process: 1 – resultant pressure exerted on the metal column; 2 – the pouring gate; 3 – preform; 4 – mould ring; 5 – gasket; 6 – vacuum chamber; 7 – suction stub valve. Arrows indicate the direction of pressure

The dependency below shows the condition that makes possible the process described:

$$\Delta P = P_m + P_p - P_k \quad (1)$$

where: P – resultant pressure; P_m – metallostatic pressure; P_k – capillary pressure; P_p – air pressure acting on the metal column, resulting from the pressure difference between the chamber and the atmosphere.

The infiltration process takes place when:

$$\Delta P > 0 \quad (2)$$

The process carried out (its result being the casting produced / machinery parts manufacturing [1-4, 24, 28] – Fig. 8) was evaluated according to two criteria:

– the geometry of the castings obtained in relation to the set parameters (dimensions of the female mould and of the reinforcing preform), and
– the metallographic structure observed on the polished sections performed in the lower and upper parts obtained from composite castings.

Geometric parameters were evaluated by comparison of the diameter ø and the height h of the obtained casting with the elements used in the process of casting preparation: female mould and reinforcing preform. During the visual and metallographic evaluation, the degree of saturation of the castings was assessed. The specimen from the casting to be used in the evaluation of the saturation of the reinforcement was cut apart so as to allow a metallographic evaluation of the axial polished cross-section of the specimen. NIKON Optiphot-100 optical microscope was used to evaluate the metallographic structure of the samples.

Fig. 8. Composite casting with the gating system

3. Results and analyses

The analysis of the geometry of the female mould, reinforcing preform and the casting (Table 2) showed that the proposed method of making castings allows precise castings to be obtained. During the analysis, it was found that the shrinkage of the reinforcing preform in relation to the female mould did not exceed 0.7%, and the difference between the dimensions of the composite casting and the reinforcing preform was smaller than 0.25%. These values are smaller than those found in unreinforced castings [6-7], which allows for precise shaping of the geometry of composite castings.

No unfilled parts of the reinforcing preform were found during the inspection of the specimen. The casting was characterized by a uniform surface and good shape reproduction.

The analysis of metallographic polished sections (Fig. 9 and 10) also yielded positive results. No porosity was found on the examined metallographic polished sections.

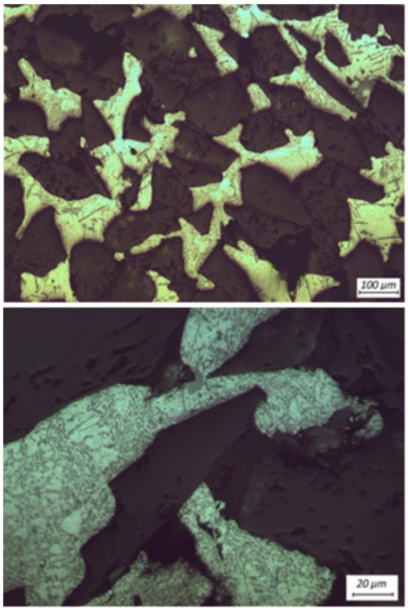

Fig. 9. Composite casting structure – analysis carried out on the upper part of the casting

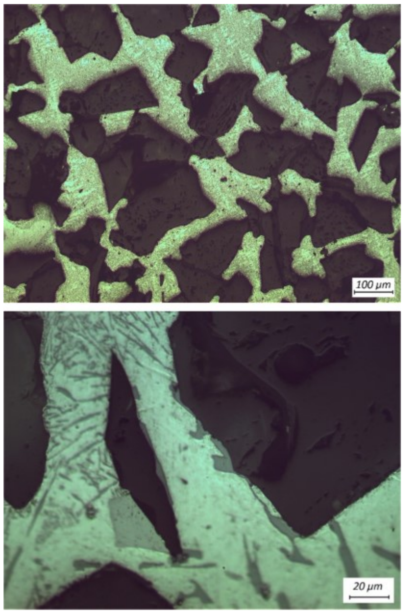

Fig. 10. Composite casting structure – analysis carried out on the bottom part of the casting

4. Conclusion

It can, therefore, be said that, as predicted in previous calculations, the reduced pressure values used allowed the reinforcement capillaries to be completely filled.

The proposed method is, therefore, suitable for the preparation of precision composite castings with complex shapes.

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Table 2.
Geometric analysis of the casting

Item		Diameter Ø				Height
		$Ø_{Top}$	$Ø_{Midpoint}$	$Ø_{Bottom}$	$Ø_{medium}$	h medium
		[mm]	[mm]	[mm]	[mm]	[mm]
1	the female mould for the preform	37.93	37.45	37.70	37.70	25.38
2	the preform after sintering and impregnation	37.64	37.68	37.35	37.46	25.40
3	composite casting	37.65	37.38	37.28	37.44	25.33
	the difference in the size of matrix and preform				0.24	–0.02
	SHRINKAGE of the reinforcement [%]				0.628	–0.079
	the ratio of the casting dimension to the reinforcement dimension				99.95	99.75
	SHRINKAGE of the casting [%]				0.053	0.249

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