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Manufacturing of Composite Castings by the Method of Fused Models Reinforced with Carbon Fibers Based on the Aluminum Matrix

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Abstract

The paper presents an attempt to produce aluminum matrix composites reinforced with short carbon fibers by precision casting in a chamber with a pressure lower than atmospheric pressure. The composite casting process was preceded by tests related to the preparation of the reinforcement. This is related to the specificity of the precision casting process, in which the mold for shaping the castings is fired at a temperature of 720°C before pouring. Before the mold burns, the reinforcement must be inside, while the carbon fiber decomposes in the atmosphere at 396°C. In the experiment, the reinforcement in the form was secured with flake graphite and quartz sand. The performed firing procedure turned out to be effective. The obtained composite castings were evaluated in terms of the degree of alloy saturation and the displacement of carbon fibers. As a result of the conducted tests, it was found that as a result of unfavorable arrangement of fibers in the CF preform, the flow of metal may be blocked and porosity may appear in the casting.

Keywords: Castings, Metal matrix composite (MMC), AlSi matrix, Casting by melted models

1. Introduction

Metal matrix composites (MMC) can be produced by introducing ceramic particles, fibers or whiskers into a metal matrix by mechanical mixing, and then shaped by filling the prepared mold with a liquid suspension or by liquid pressing [1-3]. The production of cast composite elements with an extensive geometric form requires the use of geometrically complicated forms. This may refer to both the mold cavity itself and the cavity together with the gating and feeding system [4]. Another method of producing MMC is powder metallurgy, where previously mixed components (short fibers, particles, metal) are hot pressed [5-7]. Another group of MMC are composites with saturated reinforcement, in which the reinforcement is a preform (made of ceramic sinter or short or long fibers) [7, 8]. The technology of metal infiltrated composites consists in filling the pores of the reinforcement with liquid metal or alloy. The main difficulty in the infiltration process is to determine the shape of the channels through which the liquid metal flows filling the composite reinforcement element, especially when the reinforcement structure presents geometric chaos [9-11]. This is the case when the reinforcing element is made of, for example, thin, compressed ceramic fibers. Poor channel filling during infiltration can also be caused by too low infiltration pressure and/or too low temperature of the liquid alloy or reinforcement. An additional problem is usually poor wettability of the reinforcement material by the metal.

Very often used reinforcement material due to its mechanical properties are carbon fibers - CF. In combination with aluminum alloys, a composite of low density and high mechanical strength is obtained [12]. The process of manufacturing aluminum composite castings reinforced with Al/CF carbon fibers is produced by placing in a CF mold and then filling the mold under pressure with a liquid alloy. Molds and reinforcement are usually preheated before the infiltration process [11, 13, 14]. Poor wetting of the reinforcement material requires the use of external pressure for infiltration, otherwise defects in the form of discontinuities of the composite structure will occur [15-17]. In order for the required process of liquid metal to flow into the preform and eliminate porosity in it, the following condition should be met in which the value of P_R - resulting pressure will be:

$$P_R > 0 \tag{1}$$

and the value:

$$P_R = p_c - p_g + p_m$$

where:

p_c – capillary pressure

p_g – gas pressure in the reinforcement pores

p_m – sum of pressures exerted on the metal

The value of the capillary pressure can be calculated according to the Young-Laplace equation [18]:

$$p_c = \frac{2\sigma}{r} cos\theta \tag{2}$$

where:

σ – surface tension of the metal [N/m]
θ – extreme wetting angle of the reinforcement material by the metal [°]
r – capillary radius

In a situation where the space is limited by fibers, as in the case of CF preforms, according to the diagram shown in Fig. 1, the formula will take the form:

$$p_c = \frac{2\sigma}{d_{min}} cos\theta \tag{3}$$

then:

d_{min} – the smallest distance between the fibers

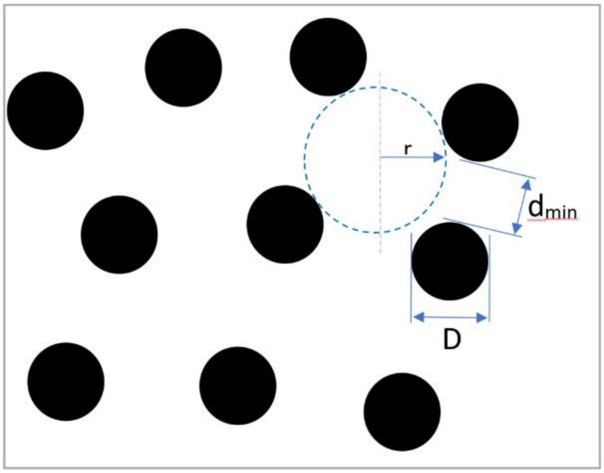


Fig. 1. An example layout for a space limited by reinforcement fibers (of diameter D), where d_{min} is the smallest distance between them

In the further part of the paper, research related to the production of the Al/CF composite in vacuum-infiltrated ceramic molds is presented. The infiltration process was preceded by calculations related to the determination of the capillary pressure value (3) in order to determine the relationship (1). To determine the relationship (1), the values of the surface tension of the alloy and the contact angle were adopted: θ = 126° and σ = 865 mN/m [19-22]

2. Materials and methods

For the production of Al/CF composite castings, the precision casting method was used, using carbon fiber in the form of blocks of pressed short fibers with a diameter of approx. 10 µm and an average length of 2 mm, produced by Carbon Group. The fibers were pressed under a pressure of 0.75 MPa, which allowed to obtain an apparent density of 0.15 g / cm3. The dimensions of the preform used were 20 mm x 20 mm x 30 mm (fig. 2). The matrix was formed by aluminum alloy EN AC-44300 (AlSi12(Fe)) - Cast Aluminum. Casting gypsum powder from Gold Star Powders and SuperCera casting wax from Castaldo were used to produce the mold and pattern.

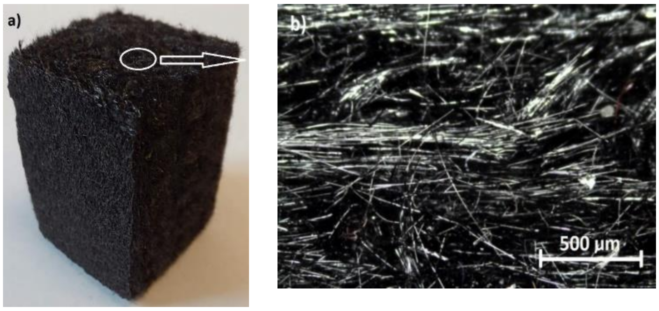


Fig. 2. View of the CF sample (a) and the microstructure (optical microscopy) of the carbon reinforcement (b)

The preform was impregnated with wax by immersion. The wax created an airtight coating, filling all the pores in the reinforcement structure. The presence of wax prevents the gypsum mass from flowing between the pressed fibers and makes it possible to obtain the desired structure of the casting. The insert was then placed on the wax sprue pattern of the master casting (Figure 3). A set of standards was placed in a metal pipe with holes and poured with casting gypsum mass.

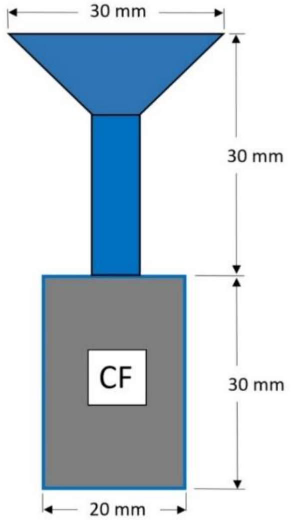


Fig. 3. Diagram of the CF insert mounted on the wax pattern of the main casting

After the plaster mold had solidified, the wax was melted at 150 °C. The free space in the mold that appeared after melting the wax was filled with flake graphite, and then the whole set was placed in a ceramic container and covered with quartz sand according to the scheme shown in Fig.4.

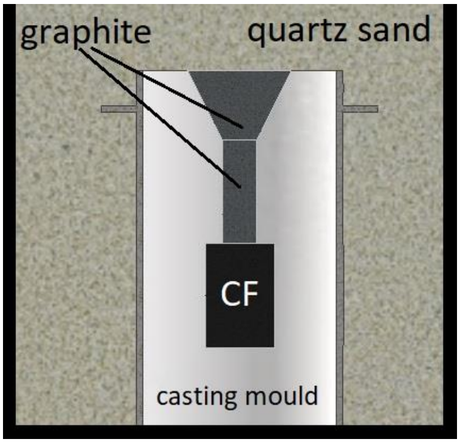


Fig. 4. Scheme of mold protection during the firing process

This procedure was carried out to protect the carbon fibers from air, as carbon fibers degrade at 396 °C due to oxidation. The protected mold was placed in an oven which was heated to 720 °C and then cooled to 390 °C. The process took 12 hours. After the ladle is taken out of the furnace, it is air-cooled to 350 °C (Fig. 5).

Fig. 5. Casting before moulding process

Then, the graphite was removed from the gating system and the mold was placed in a vacuum chamber (Fig. 6). The eutectic aluminum alloy AlSi12, cut from ingot, was melted in a graphite crucible at a temperature of 720 °C and after obtaining a pressure value in the chamber of 2000 Pa, the mold was poured with liquid aluminum alloy, maintaining a vacuum in the chamber until the casting solidified.

Fig. 6. Scheme of the vacuum casting station: the red arrow indicates the direction of pouring and the atmospheric pressure acting on the metal

The first stage consisted in saturating the reinforcing phase with a liquid matrix alloy, as well as cooling and solidification of the casting, while the second consisted in removing the casting from the mold and finishing (similarly as in the case of castings made of traditional materials). The casting was cleaned of sand residue, the gating system was removed and initially evaluated for the presence of shape defects.

CT measurement

The assessment of the shape and distribution of fibers in the reinforced cast was made using a micro-CT device. The computer tomograph v|tome|x s produced by General Electric was used during studies. To illustrate the internal structure and distribution of fibers, a nanofocus lamp was used, which allowed to obtain a voxel with a size of 2.9 µm. The measurement time was 245 minutes with power parameters of 70 kV and 200 µA. Fiber distribution evaluation was performed using Volume Graphics 3.0 software.

Optical microscope

The tests of the preform were carried out on the Baty Vision 2510 optical measuring machine. The device, thanks to a very precise optical system, allows to obtain a clear picture of the distribution of the tested preform fibers. The study of the structure of the composite casting was performed on a Nicon Eclipse MA200 metallographic microscope equipped with the NIS-Elements BR program.

3. Results and discussion

The CT microtomography of the sample taken from the Al/CF casting (Fig. 7) was performed to determine whether the flowing metal did not lead to the dislocation and damage of the carbon fibers of the reinforcement. It can be concluded that the arrangement and distribution of the fibers is similar in orientation to the structure of the input material, while the darker areas visible in the photo running linearly along the fibers indicate the presence of porosity in the casting.

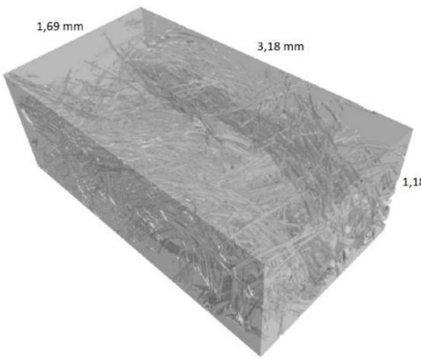
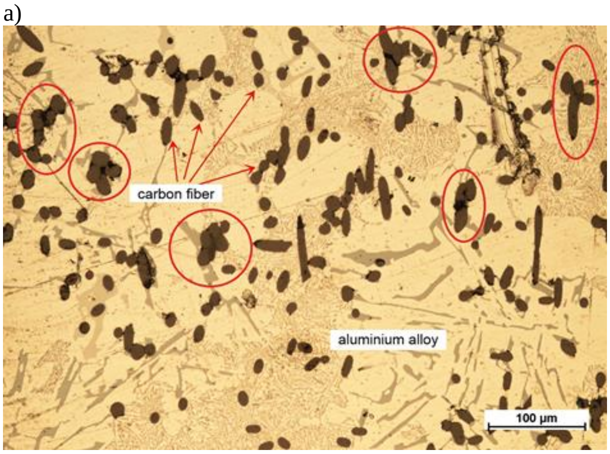


Fig. 7. Microtomography of a sample cut from an Al/CF cast with visible areas of structure discontinuity (dark area)

Metallographic analysis of the micro-section image confirmed the presence of porosities located mainly in places of fiber clusters and their entanglements, these areas are marked with circles in Fig. 8a. The areas of the composite in which there are no weaves of carbon fibers and in which the flow of metal between the fibers was undisturbed are characterized by full connection at the metal/reinforcement border. The observations also show that defects appear already at the contact of two fibers, which can be seen in Fig. 8b, where wedge-shaped capillary angles of 30 and 43 degrees are marked in the areas where the fibers were not wetted.

a)



b)

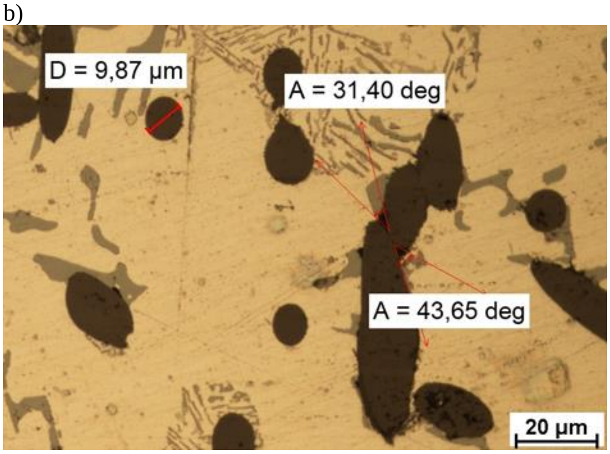


Fig. 8. Micrographs of the Al/CF composite with marked areas of porosity - a), wedge-shaped metal-free capillaries – b)

During the filling of the mold with liquid metal, along with the saturation of the reinforcement, a number of phenomena occur that are characteristic of filling the molds during the production of castings from classic materials. These are: metal flow in non-reinforced mold spaces, re-creation of mold shapes, and casting surface formation. During saturation, in addition to overcoming the initiation pressure, the inflow of metal in the spaces (channels) with the most favorable flow conditions (these places are located in areas with locally reduced "packing" density of short fibers), after the increased hydraulic resistance, the decisive stage occurs - filling the capillary spaces formed by fibers that are in contact or close to each other.

Therefore, in the case of poor wetting of the surface of the reinforcement with liquid metal, in the capillaries formed in the reinforcing preforms built of disordered fibers, where there are numerous areas of fiber contact, there are spaces that require high pressure values - theoretically approaching infinity to fill them completely with liquid metal. An example of such areas created by disordered fibers is the diagram shown in Figure 9 a) and b). Hence, it is impossible to completely fill the spaces between the blocks, and any saturated composite with reinforcement formed of disordered fibers will be porous.

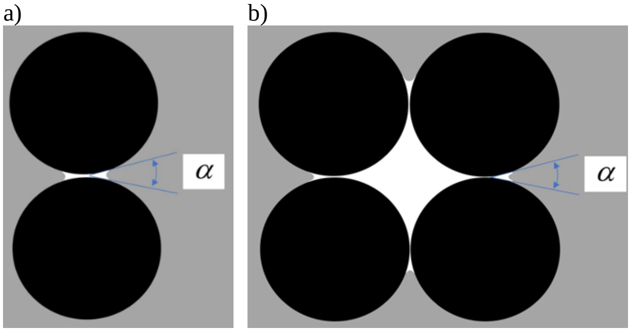


Fig. 9. Two fibers forming a capillary that is difficult to wet – a), fibers blocking the flow of metal - b)

Applying pressure to the metal higher than necessary for the required (incomplete) hollow fill is undesirable as it may lead to deformation or displacement of the reinforcing preform. It also introduces excessive stresses in the fibers in the front areas of the flowing metal, which can lead to cracks and breaks in the reinforcement structure.
In the analyzed case, the capillary pressure Pc according to relation (3) for capillaries d_{min} = 11 is about minus 92500 Pa, and the pressure difference between the atmosphere and the chamber is 98500 Pa. The value of P_R is therefore 5500 Pa and meets the condition (1) which ensured the flow of metal and confirms previously adopted assumptions.

4. Conclusions

Determining and determining the conditions of reinforcement saturation in the production of Al/CF castings using the melted model method enables the production of shaped precision castings, thus minimizing the waste treatment. The research carried out in the presented work allows us to draw the following conclusions:

- The use of potting with the use of a vacuum chamber ensures the filling of capillary spaces and obtaining good quality composites.
- It is possible to make an Al/CF composite casting using the melted model method, provided that the CF fibers are adequately protected against oxidizing agents during the thermal treatment of the mould.
- It is necessary to determine the value of the angle α of the forming capillary at the junction of fibers in order to determine the conditions of metal flow, which will be the subject of further research.

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