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ARCHIVES
of
FOUNDRY ENGINEERING

DOI: 10.24425/118806

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

ISSN (2299-2944)
Volume 18
Issue 1/2018

23 – 28

5/1

Determination of Duration and Sequence of Vacuum Pressure Saturation in Infiltrated MMC Castings

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Received 01.12.2017; accepted in revised form 10.12.2017

Abstract

The paper presents a detailed description of one of the newest methods of vacuum saturation of reinforcing preforms in gypsum molds. As an appropriate selection of the infiltration time is a crucial problem during realization of this process, aim of the analysis shown in the paper is to present methods of selection of subatmospheric pressure application time, a sequence of lowering and increasing pressure, as well as examining influence of structure of reinforcing preforms on efficiency of this process.
To realize the aim, studies on infiltration of reinforcing preforms made of a corundum sinter of various granulation of sintered particles with a model alloy were conducted. The infiltration process analysis was carried out in two stages. The first stage consisted in investigation of influence of lengthening of sucking off air from the reinforcing preforms on efficiency of this process. In the second stage, an analysis of influence of a two-staged infiltration process on saturation of the studied materials was conducted.
Because the studied preforms were of similar porosity, the obtained differences of the saturation level of particular preforms have shown, that the saturation process is influenced mostly by size of pores present in the reinforcement. Because of these differences, each reinforcement type requires individual selection of time and sequence of the saturation process. For reinforcements of higher pore diameter, it is sufficient to simply increase air sucking off time to improve the saturation, while for reinforcement of smaller pore diameter, it is a better solution to apply the two-staged process of sucking off air. Application of the proposed analysis method allows not only obtaining composite castings of higher quality, but also economical optimization of the whole process.

Keywords: MMC, saturation, Determination of process parameters, Time of infiltration, Gypsum mold

1. Introduction

Infiltrated metal composite materials have found many applications due to their high formability and other properties [1-8]; however, the production of these materials presents many problems. The main problem is in obtaining an adequate degree of saturation of the reinforcing preforms, meaning the percentage of pores which are filled with metal in the preform, thereby limiting the porosity (number of non-filled cavities) of the composite material.

Different infiltration methods are used to achieve the highest degree of preform saturation:

- free infiltration, which is rarely used in practice due to the poor wettability of the reinforcement material by the metal matrix [2-4],
- high pressure infiltration, in which the high infiltration pressure can cause deformation or destruction of preforms [1,3-7], and
- low pressure infiltration, such as: gas pressure infiltration [5,6] or centrifugal infiltration [4-9], and
- vacuum pressure infiltration [2-4,5] which is currently the most commonly used method.

Vacuum pressure infiltration can be implemented by several distinct methods. Figure 1 shows the design and working principle of the most commonly described vacuum infiltration process.

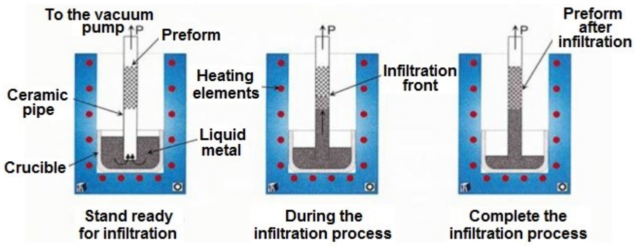
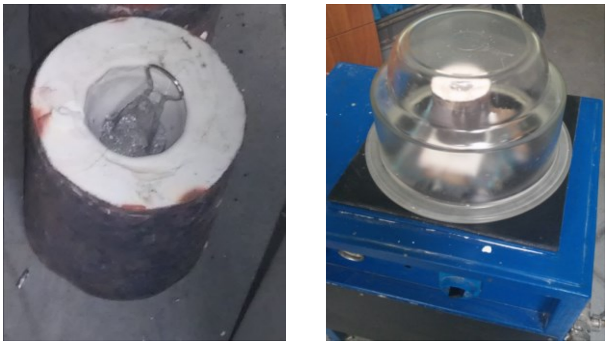


Fig. 1. Schema of vacuum pressure infiltration [4]

In this method, the infiltration is carried out using atmospheric pressure or increased gas pressure. The reinforcing preform is placed in a mould consisting of a ceramic tube or a metal cylinder. A vacuum pump is connected to one end of the mould and the other end is placed in a metal bath. After the vacuum pump is switched on, metal is drawn into the preform. Additional gas pressure, applied to the surface of the metal, facilitates and speeds up this process. The main limitations of this method are the shapes of the casts obtainable in moulds constructed in this manner, due to the necessity for using pass-through moulds, and the cost of equipment.



a) b)

Fig. 2. Vacuum pressure infiltration: a) plaster mould, b) view of infiltration equipment

An alternative method is infiltration of preforms in plaster moulds (Figure 2). Plaster moulds, due to their high strength and low permeability, are ideal for use in conditions of variable pressure and saturation, in addition to allowing virtually any shape and size of casts to be obtained.

This method uses disposable moulds, which are prepared in a manner almost identical to casting; however, depending on the shape of the reinforcement and its location within the cast, reinforcing preforms are infiltrated with wax, connected with the gating system and poured with plaster mass or placed in the mould only after firing. In the case of strongly oxidizing reinforcement materials, such as carbon fibre, a protective atmosphere should be employed during firing of the combined preform and mould so as to avoid damaging the reinforcement material. Moulds fired and prepared in this way are then immersed in molten metal and placed inside a vacuum chamber.

When removing air from the chamber the reinforcing preform is also emptied of air. This process works in a similar manner to vacuum refining. Opening the valve and increasing the chamber pressure pushes the molten metal into the pores of the reinforcing preform. Thanks to the prior use of vacuum pressure, this step is easier and allows for casts with satisfactorily low porosity to be obtained.

The main parameters which affect the operation of the process are:

- temperature of the mould, reinforcing preform and metal matrix,
- the vacuum pressure applied, and
- time taken to remove the air from the reinforcing preform (in the vacuum chamber).

In the study presented below, we have analysed the method to determine the vacuum duration and the influence of the infiltration process on the porosity of composite casts produced by this method.

2. Findings

A test determination of infiltration time was carried out for two composites (Figure 3) saturated with low fusible TBC20 test alloy (Table 1), reinforced with sintered alumina preforms with varying grain-size distributions (Figure 4).

Fig. 3. Composite cast ø=20mm, h=30mm: matrix TBC20, reinforcement sinter alumina powder

Table 1.
Chemical composition of metal matrix [PN-91/H87203]

TBC20 (BiPb30Sn20)			
Chemical composition		Pollution	
Bi	49-51%	Fe	~0,05%
Pb	29,5-30,5%	Cu	~0,05%
Sn	19,5-20,5%	As, Sb	~0,01%

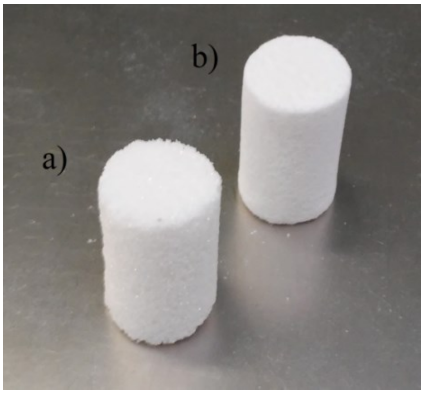


Fig. 4. Reinforcement preforms a) FEPA 046, b) FEPA 100

The use of reinforcing preforms allows for a comparison of the influence of the composite reinforcement structure on the analysed process. These preforms are characterized by identical surface properties and very similar porosities (Table 2) but they have different pore sizes (Figure 5 a-b). Table 1 shows produced composites with clearly visible pore sizes - it presents theoretical mean number of pores calculated by authors based on [10-11]

Table 2.
Reinforcing preforms - material characteristics

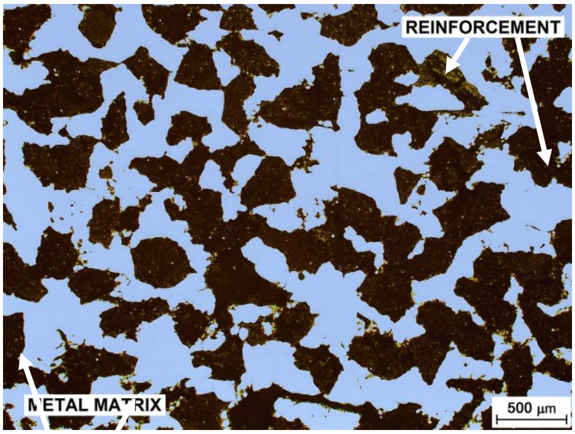
Symbol of the reinforcing preform corresponding to the grain numbering	Grain-sizes of sintered particles [μm]	Average porosity of the preform [%]	Theoretical mean size of pores [10-11] [μm]
FEPA 046	425 – 355	47.8	187.2
FEPA 100	150 – 125	46.6	64.6

The vacuum process (Table 3) consists of two phases. In the first phase, the air is removed from the chamber, in which the mould is placed, until a set vacuum pressure is reached. The duration of this phase depends primarily on the design of the station and the throughput of the vacuum pump. The second phase occurs at constant pressure and determines the final result of the saturation process.

Table 3.
Parameters of the infiltration process

temperature of the mould	~423K (~150ºC)
temperature of the reinforcing preform	~423K (~150ºC)
temperature of the metal matrix,	~423K (~150ºC)
underpressure	960 hPa

a)



b)

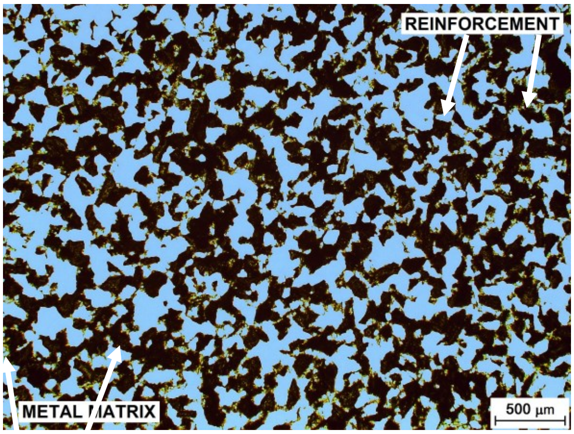
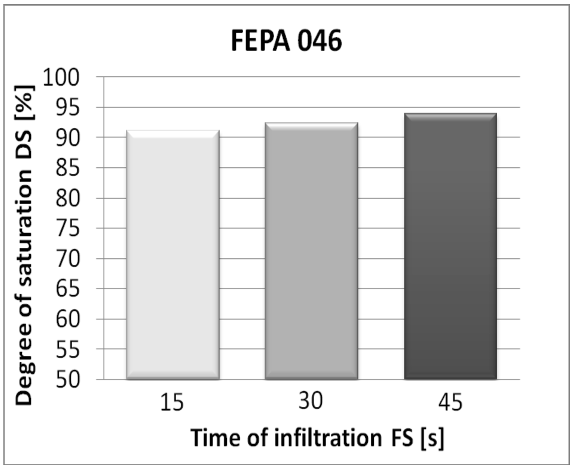


Fig. 5. The structure of TBC20 alloy matrix composite reinforced with preforms made of sintered alumina powder with varying grain-sizes: a) FEPA 046, b) FEPA 100, optical microscopy magnification as shown in the figure.

In the course of this study, it was found that the optimal duration of this phase depends on the structure of the reinforcing preform and increasing the duration does not always contribute to reducing the porosity of the obtained composite cast (Figure 6). An analysis of the degree of saturation of the reinforcing preforms was carried out by the gravimetric method in accordance with [1-4,9-11].

a)


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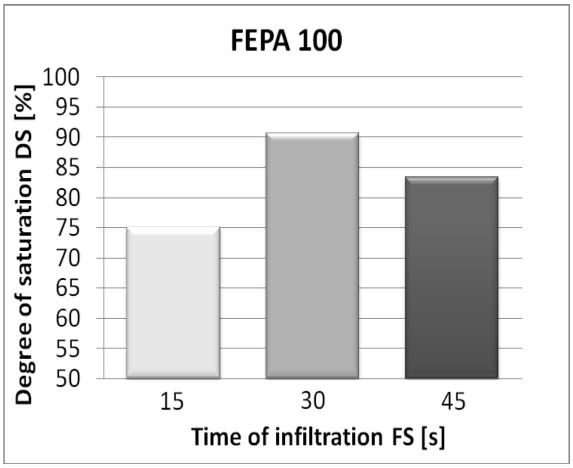


Fig. 6. TBC20 alloy degree of saturation (DS) of composite preforms made of sintered alumina powder with varying grain-sizes: a) FEPA 046 and b) FEPA 100

Figure 6 shows that, in the case of composite casts reinforced with preforms made from sintered alumina with FEPA 046 grain size, an increase in infiltration time has the beneficial effect of increasing the degree of saturation and, consequently, decreasing the porosity (Figure 7).

On the other hand, in the case of the composite reinforced with preforms made from sintered alumina with FEPA 100 grain size, which is characterised by smaller pores, extending the infiltration time to 30 seconds results in an increase in the degree of saturation, but as it is further extended to 45 seconds, a decrease in saturation occurs [1-3, 5-7]. Because the vacuum chamber is not heated, this decrease is most probably caused by beginning of the crystallization process. In the case of the FEPA 046 reinforcement, occurring crystallization nuclei and first crystals are of small importance, due to higher pore diameter (Table 2). However, in the case of the FEPA 100 reinforcement, the pore size is much lower and occurring crystallization nuclei close the reinforcement capillaries, making full penetration of a reinforcing preform by the liquid metal impossible.

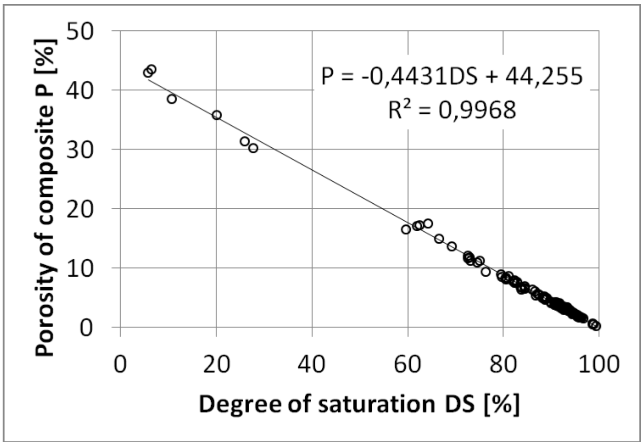
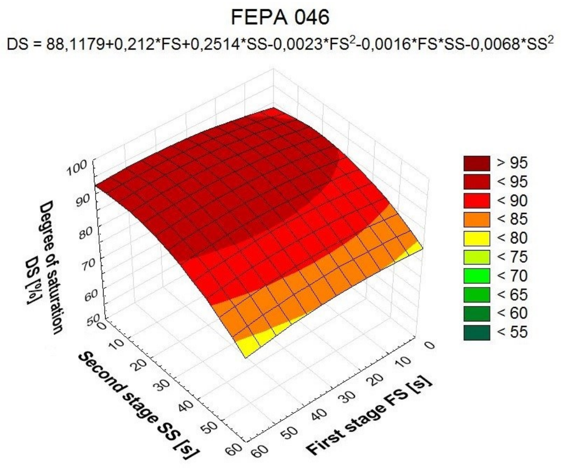


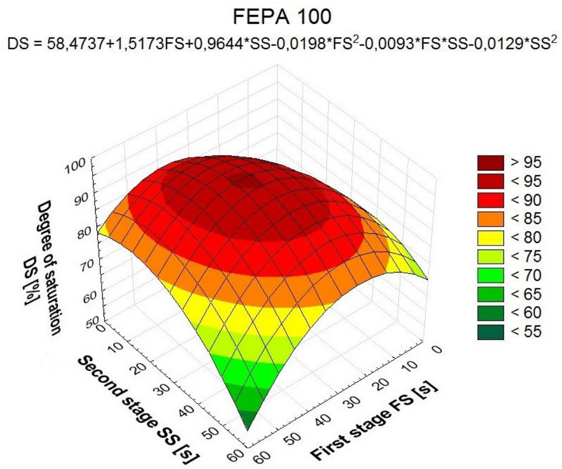
Fig. 7. Dependence of porosity of composite castings (P) on the degree of saturation of the preform (DS)

To confirm this hypothesis, an analysis of cooling curves would need to be conducted, what is very difficult in case of composites reinforced by ceramic preforms. It is problematic both to put a thermocouple inside a brittle reinforcement and consider influence of the thermocouple itself on course of the solidification process.

Preliminary enforcement of metal flow inside the reinforcement prevents closing of its pores, but does not bring satisfying results. Therefore, it was decided to find out if better results can be obtained by a two-staged infiltration process. To investigate validity of this theory, approximately 50 samples were made for each type of reinforcement, changing time of both stages by 15 seconds, keeping the other process parameters on constant levels The research has shown that applying the vacuum twice may contribute to an increase in saturation and reduction in the porosity of obtained composite casts (Figure 7); however, similar research should be carried out for each particular type of composite. The chart shown in Figure 8 shows the reason for this: in the case of one of the reinforcements made from sintered alumina with FEPA 046 grain-size, such operation results in only a slight increase, of about 4%, in degree of saturation, when the suction time is extended from 15 seconds to twice in 30 seconds; on the other hand, for reinforcements made of sintered alumina with FEPA 100 grain-size, the two-stage infiltration (30 second and 45 second) can result in an increase in the degree of saturation by up to 20%, relative to the 15 second suction period. The final decision regarding the process duration should be made after a careful analysis that includes not only the properties of the composite casts obtained, but also an analysis of the costs associated with increasing the duration of the infiltration process.



a)



b)

Fig. 8. Degree of saturation (DS) with TBC20 alloy of ceramic preforms made of sintered alumina powder with varying grain-sizes: a) FEPA 046 and b) FEPA 100 for the two-stage process (first stage FS, second stage SS)

3. Conclusions

The performed analysis of the vacuum pressure infiltration of reinforcing preforms made from sintered alumina powder with varying grain-size allows the following conclusions to be drawn:

1) Infiltration of the reinforcing preforms in gypsum molds with a model alloy TBC20, with use of subatmospheric pressure, allows obtaining castings of high level of saturation (more than 90%).
2) Level of saturation of the reinforcing preforms is dependent not only on time of the infiltration process, but also on internal structure of a preform (size of pores – Table 2, Fig. 6), while increasing the air sucking off time from a porous reinforcing preform does not always contribute to increase of saturation and reduction of porosity.
3) Due to a fact, that the saturation process is conducted in a cold vacuum chamber, the most probable cause of this phenomenon is occurrence of crystallization nuclei, limiting metal flow in reinforcement capillaries of lower diameter.
4) Increase of efficiency of the infiltration process, from 4% to 20%, may be obtained by conducting a two-staged air sucking off process from the porous reinforcement. However, a series of tests must be performed each time, to establish an optimal cycle of infiltration. Economic justification of lengthening of the saturation process must also be performed.
5) Because the reinforcing preforms made of a sintered corundum powder had similar porosity (1% difference), the conducted studies indicate, that in case of the composite reinforcements, size of pores and not the porosity (Table 2) is a main factor deciding of efficiency of the infiltration process (Fig. 8).
6) The method of selecting time and sequence of the process of lowering and increasing the saturation pressure presented in the paper is a time-consuming one. However, it can be applied for selection of the saturation process parameters for different types and materials of reinforcing preforms, with all technical alloys.

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