Porosity of Metal Infiltrated Composites – An Attempt at the Problem Analysis

Jacek Jackowski
Poznan University of Technology

Janusz Grabian
Maritime University of Szczecin

1. INTRODUCTION

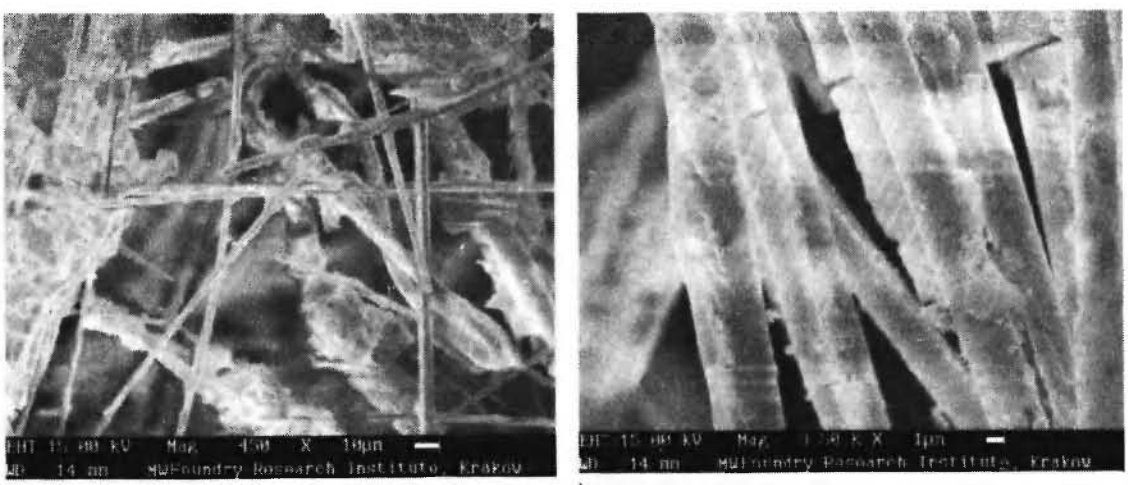
One of the major requirements that cast metal semi-finished products intended for machine parts have to satisfy is the compactness of structure. The compactness is particularly hard to obtain in the case of composite machine components produced by means of reinforcement infiltration with a liquid metal. This paper examines the way porosity is formed in a composite the reinforcement of which consists of profiles of pressed ceramic fibres of thickness ranging to several μm. Their chaotic arrangement makes geometric description of the obtained porous material impossible.

2. POROSITY OF METAL INFILTRATED COMPOSITES

Composite porosity forms during the liquid metal infiltration of a porous reinforcement profile (an example of its structure is shown in Fig. 1) and during the metal solidification. The porosity is a sum of porosities created for various reasons:

$$S_T = S1+S2+S3+S4$$

The component porosities of the sum are presented in Fig. 2 in diagram form.



a b

Fig. 1: The structure of aluminosilicate fibre reinforcement named SIBRAL (made by the Czech maker KERAUNION) used in attempted production of infiltrated composites: a-magnified 450x; b-magnified 3500x. The photos were taken at the Foundry Institute of Cracow

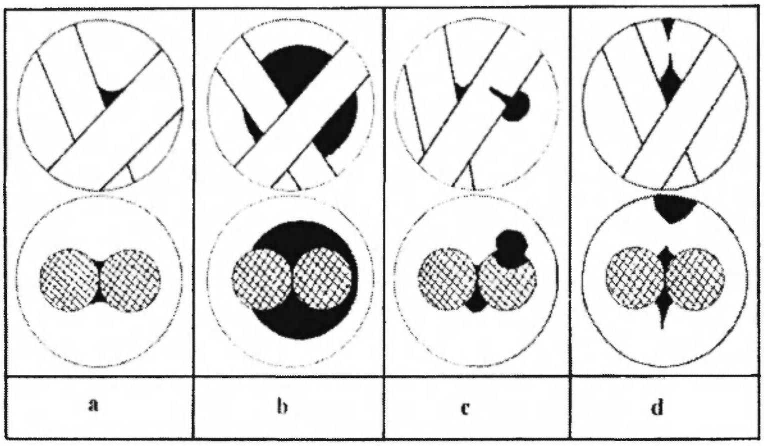


Fig. 2: Diagrams of hollow spaces (discontinuities) in the microstructure of infiltrated composites caused by: a-insufficient filling of the reinforcement with the liquid matrix; b-formation of gas bubbles during reinforcement infiltration; c-evolution of gas solved in matrix metal; d-matrix contraction.

2.1. Infiltration of the matrix metal reinforcement

Poor wetting of the reinforcement by metal makes it necessary to execute infiltration under high pressure. Attempts to infiltrate the composite reinforced with SIBRAL (Fig.1) by means of a model matrix (Wood's alloy /1/ and the AlSi11 alloy /2/ have shown that adequate infiltration pressure can be determined from the value of the so called conventional geometric parameter of reinforcement determined from the equation presented in Fig. 3.

The conventional parameter, calculated bv the Young-Laplace equation, for the examined reinforcement was 0,055 μm. Its corresponding pressure values of infiltration with AlSi11 and copper were, respectively, 29 MPa and 32 MPa. The investigation has also shown an important influence of infiltration time on composite density /4/. The steady optimized infiltration pressure applied in the 0÷300 seconds time range caused changes in mean porosity of obtained composite samples (infiltrated in isothermal conditions) ranging from 2.3 to 0%. Mean values are given due to the fact that when infiltration times were short some samples had higher porosity. This refers to cases when the temperature of the reinforcement and the metal differed during the

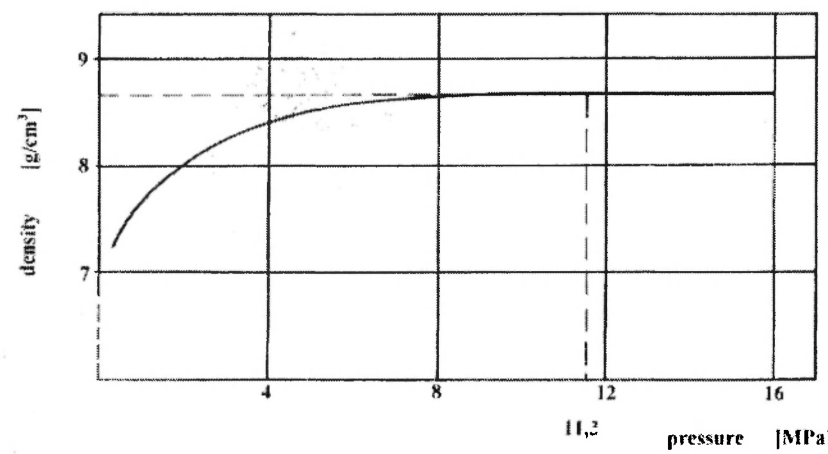


Fig. 3: Composite density (SIBRAL - Wood's alloy) vs. infiltration pressure

infiltration. When the reinforcement temperature is lower than that of the metal, the latter may solidify in reinforcement fibres thus deteriorating infiltration conditions.

2.2. Gas occlusions formed during infiltration

The filling of capillary spaces in the reinforcement proceeds with the principle of minimum resistance, i.e. first the largest capillaries are filled. As the time passes (with continuous action of the pressure) smaller and smaller capillaries get filled (Fig. 4). It is very probable that gas (air) occlusion will be closed within the reinforcing element (Fig. 2b), but it is difficult to estimate the amount of gas in the occlusions. The occluded gas quantity in the composite casting depends on the direction of metal flow during infiltration and the process of matrix solidification.

Fig. 5 presents an example of how these factors act. When the reinforcement is filled from below, there are good conditions for removing the gas from the casting and possible occlusions are moved to the raiser head through the solidification front. This fact is confirmed by the raiser head cross-sections (favorable to the removal of gas occlusions) in the castings made as shown in Fig. 6.

The cross-sections reveal both the effects of contractions concentrated in the area of the latest solidifying metal and large gas bubbles pushed to this area through the solidifying metal front. It can be estimated that each cubic centimetre of gas occlusions closed in the reinforcement infiltrated with the aluminum alloy and heated to the temperature equal to that of the fully infiltrated matrix metal (700°C) at the pressure of 30 MPa may cause porosity in the composite material expressed as 0.003 cm^3 spaces. This volume may increase approximately threefold if the reinforcement is not heated before the infiltration starts.

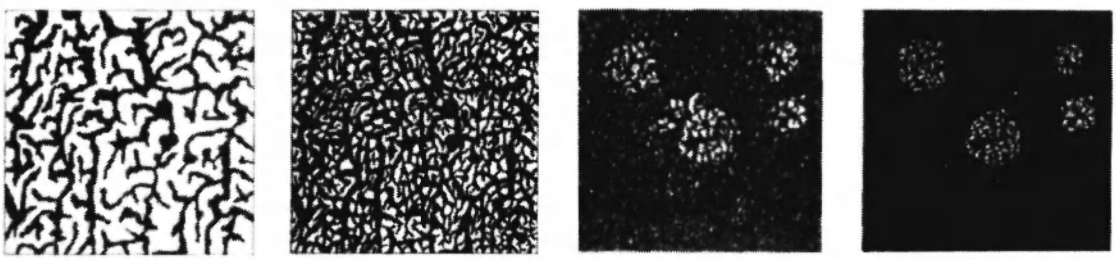


Fig. 4: A process of composite reinforcement infiltration

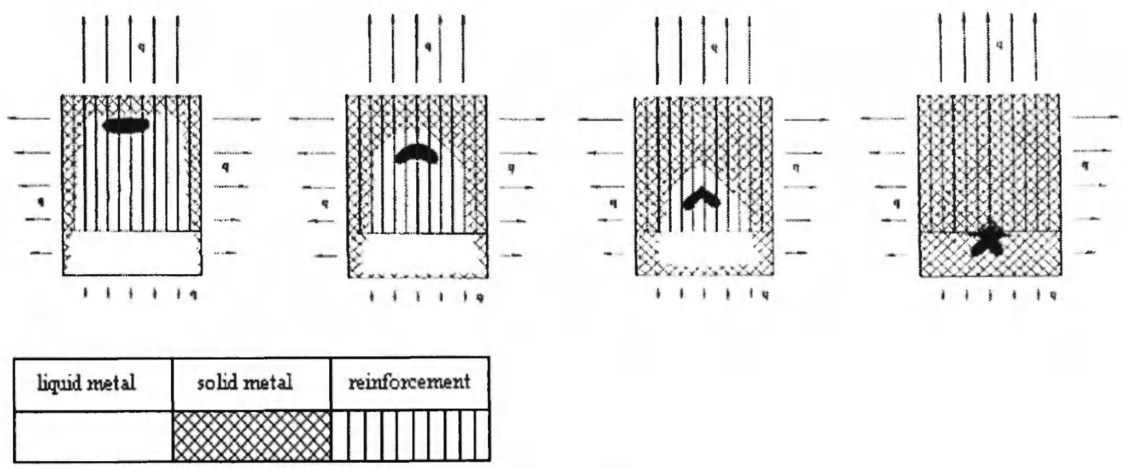


Fig. 5: Filling solidification of a composite casting

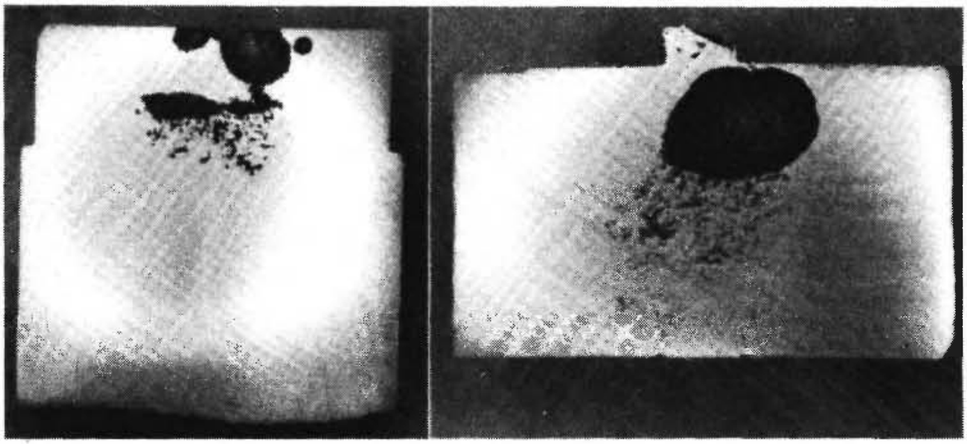


Fig. 6: Effects of matrix metal solidification and movements of gas occlusions found during attempts to make samples of the composite infiltrated in conditions similar to those shown in Fig. 5.

This means that in the extreme case, when the total volume of the gas phase filling reinforcement pores gets occluded by the liquid metal of the infiltrating matrix, the porosity of the obtained composite will increase 0,3÷1% depending on the reinforcing component (heated or cold).

2.3. Gas evolution from solidifying metal matrix

Liquid metals and their alloys are characterized by much higher ability to solve gases than their solid phase. The relationships given by R.P. Eliot /6/ concerning the solubility of hydrogen in liquid and solid aluminium allowed for calculations presented graphically in Fig. 7. The relationships imply that the evolution of hydrogen bubbles from the liquid metal during the reinforcement infiltration is possible only when highly gassy metal is used and the infiltration pressures do not exceed 20 MPa. For higher pressure required for reinforcement in filtration no gas evolution occurs, even if the metal is extremely saturated with hydrogen.

The pressure acting on the liquid metal during reinforcement infiltration does not help nucleation and increase of gas bubbles in liquid metal. The process is

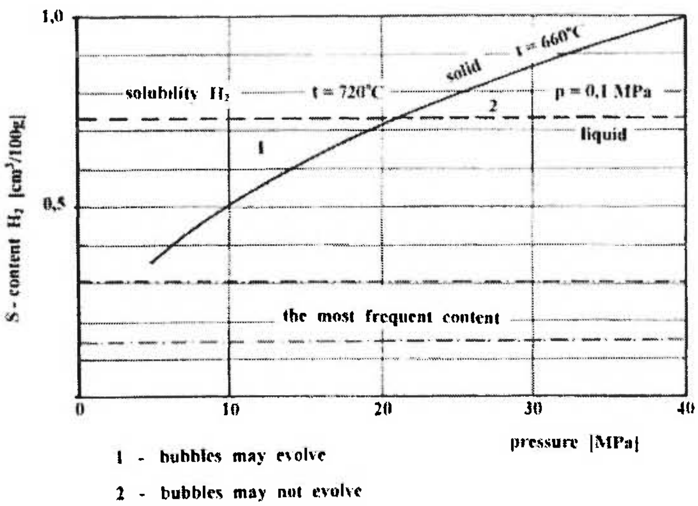


Fig. 7: Conditions for the formation of hydrogen bubbles in the AlSi11 alloy as a function of pressure

facilitated by the existence of reinforcement fibres on which nuclei of gas bubbles may form (Fig. 2c). Hydrogen found in the liquid matrix may also diffuse into unfilled capillary spaces in the reinforcement thus increasing their volume. An example of reinforcement fibres with uneven surfaces and fractures which may favour the nucleation of gas bubbles is presented in the photograph (Fig. 1b). A gas bubble with a diameter of 0.05 mm found in the composite material structure (SIBRAL- AlSi11 Alloy) is shown in Fig. 8.

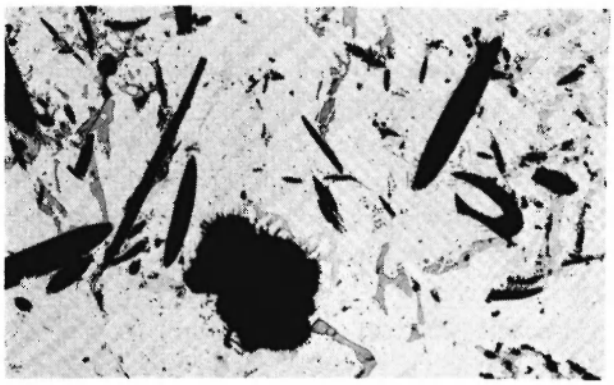


Fig. 8: A gas bubble observed in the structure of the composite structure infiltrated with SIBRAL-AlSi11. Magnified 375x

Such a bubble may be formed only in the area of lowered pressure of the solidifying metal; this kind of area may appear in the middle part of casting. Gaseous porosity may therefore make an essential contribution to the total porosity of the casting only if its feeding is poor.

2.4. Shrinkage of cooling and solidifying matrix metal

Technological properties of metals and alloys used as composite matrix are well recognized. For instance, it has been found that for the eutectic AK11 alloy the contraction of solidification is 2.66%, while the temperature coefficient of superheating contraction is 0.0149% / °C /6/. The same author has found that the overall porosity of eutectic silumin samples ranges from 3.5% to 5.5% depending on the casting temperature ranging between 680 and 780°C and the liquid alloy hydrogen content has no significant impact.

The solidification of metal matrix may cause the part of force exerting pressure in the solidifying cast(ing) to be taken over by its mostly solidified parts; in some cases parts of the casting may be isolated from the applied pressure. In such cases shrinkage porosities or microporosities may form in the casting, shown in Fig. 9, or even macroscopic shrinkage cavities, as illustrated in Fig. 6.

To avoid shrinkage-related faults of the composite casting it is necessary, similarly to other castings, to undertake adequate actions at the construction stage as well as designing technologies ensuring the proper solidification process.

3. SUMMARY

The analysed factors, deciding the porosity of metallic saturated composites, are listed in Table I. The

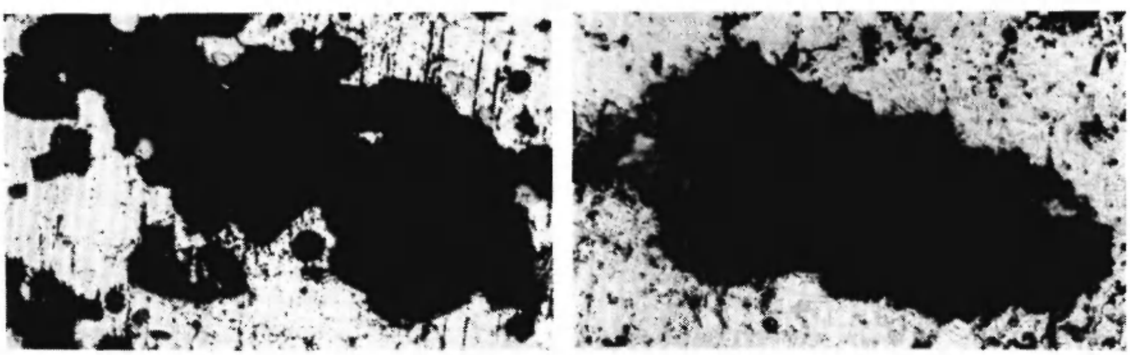


Fig. 9: Examples of shrinkage porosities found in the structure of sample of the composite infiltrated with SIBRAL-AlSi11: a-1.9mm x 0.7 (magnified 75x); b-0.3 mm x 0.1 mm (magnified 375x)

Table I

Specification of the factors inducing porosity of saturated metal composites the ratio of the porosity to total material volume, counteraction methods

Item	Porosity factors	Estimated porosity ratio	Counteraction methods
S_1	Insufficient reinforcement saturation with a liquid metal matrix	up to about 2.5%	1. Ensuring possibly the best wettability of the reinforcement-liquid metal matrix system 2. Application of sufficiently high saturation pressure 3. Ensuring sufficiently long reinforcement saturation time 4. Aiming at achieving isothermal condition reinforcement saturation
S_2	Gas occlusions in the element of saturated matrix	0.3 - 1.0 %	1. Application of maximal saturation pressure 2. Quick development of given saturation pressure 3. Aiming at achieving isothermal saturation condition 4. Reinforcement deaeration, e.g. using vacuum or negative pressure
S_3	Nucleation and growth of blisters of the gas dissolved in liquid metal matrix	minimal	1. Standard refining of liquid metal matrix
S_4	Overheating and solidification shrinkage of metal matrix	up to about 4.5%	1. Directional solidification of matrix metal 2. Efficient feeding of the casting
	Total porosity	up to about 8%	

Table specifies the values of porosity due to each of the analysed factors, as well as the ways of preventing them. Summarizing, it should be ascertained that:

1. The foregoing analysis of porosity formation in composite castings made by the method of infiltration has shown that three factors are essential:
   - insufficient infiltration of the reinforcement component with the matrix,
   - gas occlusions which may form within the composite during the infiltration of the reinforcement, and
   - shrinkage of superheating and solidification of the liquid metal matrix.
2. The infiltration pressure, chosen on the basis of the parameter proposed by the authors, i.e. conventional geometric parameter of the reinforcement, of suitable duration prevents the formation of gas porosity of the matrix and ensures proper infiltration of the reinforcement.
3. The total porosity of the examined composite may reach 8% of the composite element volume. Estimated contribution of the three previously mentioned factors in the total porosity of the infiltrated composite amounts , respectively to: 31, 13, and 56%

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ABSTRACT

One of the basic requirements imposed on semi-finished products designed for production of the parts of machines and equipment is compactness of the structure. This feature is particularly hard to achieve in the case of production of composite elements consisting of porous reinforcement (usually ceramic) and metallic matrix saturating the reinforcement (usually a technical alloy). Difficulties in obtaining a saturated composite material of ideally compact structure results, among others, from disadvantageous relationship between the properties of the components, e.g. poor or very poor wettability of reinforcement material by liquid saturating matrix, as well as from the properties of particular components, i.e. reinforcement porosity, tendency of liquid matrix metal to absorbing atmospheric gases, the change in metal volume during cooling and solidification, etc. A compact structure of composite material under saturation may also depend on the factors related to the kinetics of saturation process, as the flow of the liquid matrix through reinforcement capillaries and occurrence of gaseous occlusions or composite cooling conditions.

An analysis was performed for the process of composite casting production (saturated), consisting of ceramic (aluminosilicate) reinforcement, called SIBRAL, and a technical aluminium alloy. Particular production processes were considered, as well as the phenomena potentially affecting the formation of porosity of the composite product:

- conditions for saturation process of the porous reinforcement,
- tendency for gaseous occlusions formation during the saturation process,
- emission of gases from cooling and solidifying metallic matrix,
- shrinkage phenomena accompanying the cooling and solidifying processes of the metallic matrix.

The analysis has been performed on the basis of the experience of many authors achieved in the course of trials of production of saturated composite castings (of model and commercial character), aimed at explaining the mechanisms and conditions of forming the composite structures of saturated materials. Besides the results of the authors' own works the achievements of other persons have been utilized, as for example the data related to the properties of casting alloys used as saturating matrices. One of the authors' aims was the quantitative estimation of the contribution of particular factors to total porosity of saturated composite material. Such information is important for production engineers dealing with manufacturing of such materials, interested in not only obtaining the product of possibly the highest quality but also in optimization of the production process.

The results of the analysis showed that predominant factors deciding porosity of the composite elements produced with the method of matrix saturation with a liquid metal, specified in order of their importance, are as follows:

- insufficient reinforcement saturation with liquid

metal matrix,

- gaseous occlusions arising within the composite material in the course of saturation of the reinforcement, and
- the shrinkage arising in result of overheating and solidification of the metal matrix.

Total porosity of saturated composite material composed of fibrous aluminosilicate reinforcement and technical aluminium alloy may amount to up to 8 per cent of element volume, while the shares of the above mentioned factors in the total porosity may reach 31, 13, and 56 per cent, respectively. Remedial measures are proposed that are advisable for the purposes of reduction or elimination of porosity of composite elements.