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AN ANALYSIS OF GEOMETRIC CONDITIONS IN THE PROCESS OF INFILTRATING THE REINFORCEMENT OF CAST METAL MATRIX COMPOSITES

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An analysis was made in the first stage of producing casts from saturated metal composites, which consist in the penetration of liquid metal into the depths of the reinforcement. For most of the materials applied both the matrix and the reinforcements of the composites this process is difficult because of poor wettability of the ceramic reinforcement by liquid metal. Pressure is the enforcing factor. It is easy to select this pressure when the shape and dimensions of the space between reinforcement fibres can be geometrically described; this occurs when the reinforcement fibres are ordered. For composites of disordered fibres it is practically impossible to describe the space geometry between fibres. It has been proved that the stage of filling with metal the closed capillary spaces formed by fibres touching one another is decisive in the saturation process. It has also been proved that the process of saturating the reinforcement with disordered fibres should be examined on a macroscopic scale.

Key words: *metal matrix composites, infiltration*

Analiza geometrijskih uvjeta u procesu infiltriracijskog ojačavanja matrice kompozitnih lijevanih metala. Analiza je napravljena u prvoj fazi proizvodnje odljevaka od zasićenih kompozita metala, a to znači da je tekući metal prodro u dubinu ojačanja kompozita metala. Za veći dio materijala, i u ojačanju kompozita i u matrici, taj proces je težak zbog slabe vlažnosti keramičkog ojačanja tekućim metalima. Tlak je faktor ojačavanja. Taj tlak se da lako odrediti, ako se oblik i dimenzije prostora između vlakana koja sačinjavaju to ojačanje, mogu geometrijski opisati: to je moguće onda kad su ta vlakna pravilno raspoređena. Za one kompozite koji imaju vlakna neuredno raspoređena, praktično je nemoguće opisati geometriju prostora između vlakana. Dokazano je da je u procesu zasićivanja odlučujuća faza punjenja zatvorenih kapilarnih prostora koji su nastali međusobnim kontaktima vlakana. Također je dokazano i to da bi se proces zasićivanja ojačanja neuredno raspoređenim vlaknima trebao ispitivati pod mikroskopskim povećanjem.

Ključne riječi: *metalni kompoziti matrice, infiltracija*

INTRODUCTION

In the course of reinforcing cast metal-matrix composites, the spaces between elements making up the reinforcement are filled with liquid matrix metal [1-4]. The poor wettability of the ceramic reinforcement occurring in most cases excludes the spontaneity of the infiltration process, so it must be enforced by an outside factor - pressure. A reinforcement destined for producing infiltrated composite materials can be of different structure, and consequently different shape and size of the space filled with metal (Figure 1.). The space filled with metal, in the case of reinforcement in the shape of a bundle of parallel fibres, are capillaries of repeatable shapes and sizes. For a reinforcement made of short, disordered fibres, this space is created by a chaotic arrangement of capillaries, impossible or difficult to be described mathematically. The purpose of this report is to analyse the effect of geometry of the spaces filled with liquid metal on the value of the infiltration pressure that guarantees a definite degree of filling these spaces, also taking into consideration the physical and chemical properties of the system liquid metal - solid body (reinforcement) - gas.

INFILTRATING THE REINFORCEMENT FROM LONG ORDERED FIBRES

External pressure *p*, also called infiltration pressure, which causes infiltration of the capillary system, is determined by dependence [5]:

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$$p = p_{\text{kap}} + p_g + \Delta p \tag{1}$$

in which:

p_{kap} - capillary pressure,
p_g - pressure of the gas phase in capillary spaces,
Δp - pressure fall due to liquid flow resistance by the capillary system (kinetic resistance).

In order to determine the pressure of reinforcement infiltration, use can be made of simplified capillary models. On the basis of Young-Laplace equation the capillary pressure for cylindrical capillaries of circular section amounts to:

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

where:

σ - the value of liquid metal surface tension [N/m],
r - capillary radius [m],
θ - wetting angle [°],
α - apex angle of capillary cone [°].

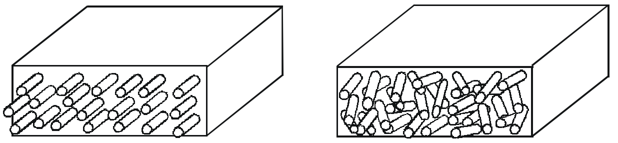

Figure 1. **Types of infiltrated composites:**
a) reinforced with long ordered fibres,
b) reinforced with short disordered fibres
Slika 1. **Tipovi infiltriranih kompozita**
a) raspored s dugim uredno raspoređenim vlaknima,
b) raspored s kratkim neuredno raspoređenim vlaknima

In composites with reinforcement made of parallel-axial fibres of circular section (Figure 1.a) the capillary canals have non-circular section. Then, the substitute radius of capillary r_z can be determined, according to the diagram shown in Figure 2. [1], [6].

For the case a) of Figure 2.:

$$r_z = \frac{1}{4}\left(\sqrt{\frac{\pi}{V_w}} - 1\right)\frac{d_w}{2} \tag{3}$$

for case b), on the other hand:

$$r_z = \frac{1}{2}\left(\sqrt{\frac{\pi}{2\sqrt{3}V_w}} - 1\right)\frac{d_w}{2} \tag{4}$$

where:

V_w - volume participation of fibres,
d_w - diameter of fibres.

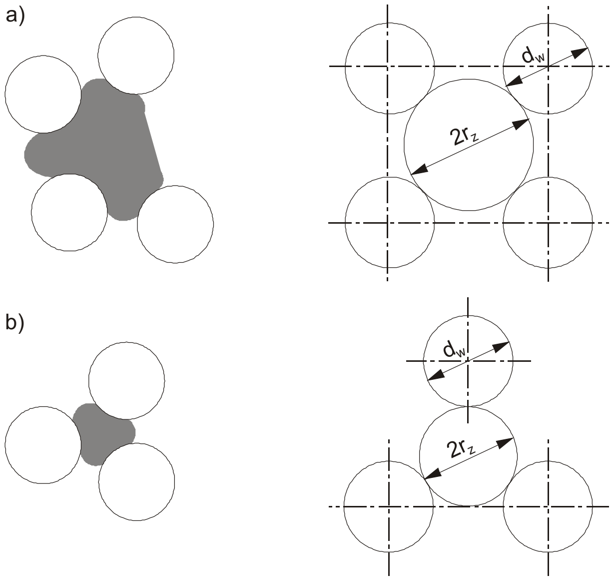

Figure 2. **Section of metal-filled capillaries and effective radius of capillaries for various configuration of fibres**
Slika 2. **Sekcija kapilara ispunjenih metalom i djelotvoran radijus za razne konfiguracije izvora vlakana**

Analysing the filling of capillary spaces on a plane perpendicular to the fibre axis attention should be paid to the fibres arranged too close to each other or contingent on one another. The occurrence of the case of fibre contact causes incomplete filling of capillary spaces with a shape close to that of a wedge, which has been presented in Figure 3. The value of capillary pressure for this case is determined by the dependence

$$p_{kap} = \frac{2\sigma}{d_w \cdot \sin\alpha \cdot \mathrm{tg}\frac{\alpha}{2}} \cdot \cos\theta \tag{5}$$

One of the means of determining the infiltration pressure value for a package reinforcing fibres arranged parallel-axially in the whole volume of the composite cast (Figure 1.a), also taking into account the kinetics of the infiltration process, is described by the following dependence [1]:

$$p = p_{kap} + \Delta p = \frac{2\sigma V_w \cos\theta}{(1-V_w) r_w} + \frac{32\mu v V_w^2}{(1-V_w)^2 r_w^2},$$

$$p_g \cong 0 \tag{6}$$

where:

V_w - volume participation of fibres,
σ - metal surface tension,
μ - dynamic metal viscosity,
r_w - fibre radius,
v - metal movement velocity.

The description of infiltrating simple capillaries of immutable section with liquid metal presented above cannot be applied to capillaries with more complicated geometry, which is the case in reinforcement moulders made of disordered fibres arranged chaotically in space.

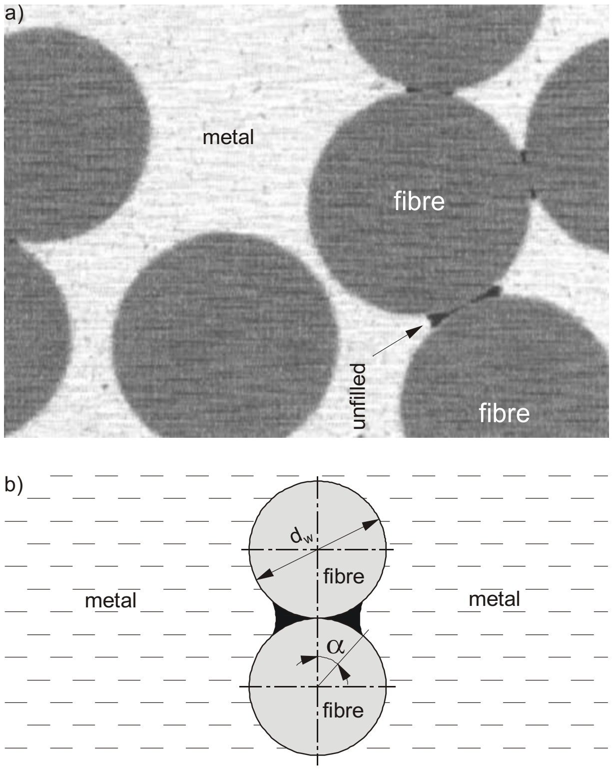

Figure 3. **Unfilled capillary space between two fibres laid in parallel**

Slika 3. **Neispunjeni kapilarni prostor između dva paralelna vlakna**

INFILTRATING REINFORCEMENT FROM DISORDERED FIBRES

The research conducted has shown that for reinforcement from short disordered fibres (Figures 1.b, 4.) the way of filling the spaces between fibres is more complex than in the case described under point 2. It has been stated that the process of filling the reinforcement moulder with liquid metal is characterized by the following successive stages:

I. Overcoming initiation pressure and flowing of the metal into spaces (channels) with the most favourable flow conditions. These places are located in areas of locally diminished density of 'packing' with fibres.
II. Filling reinforcement areas of increased hydraulic resistance.
III. Filling of capillary spaces created by contingent fibres or located in relation to each other at small distances.

The way of filling a reinforcement moulder with liquid metal (stages I and II) has been presented in Figure 4. The description of the metal flow can be based here on Darcy's filtration law, which expresses the proportionality of filtration speed to the hydraulic fall. In the infiltration stage, stage III is of decisive importance - the filling of capillary spaces with metal. Figure 5. presents the behaviour of metal in the wedge-shaped capillary in the case of poor wetting (angle θ > 90°). The phenomenon of incomplete filling of capillary spaces has been presented in Figure 7.

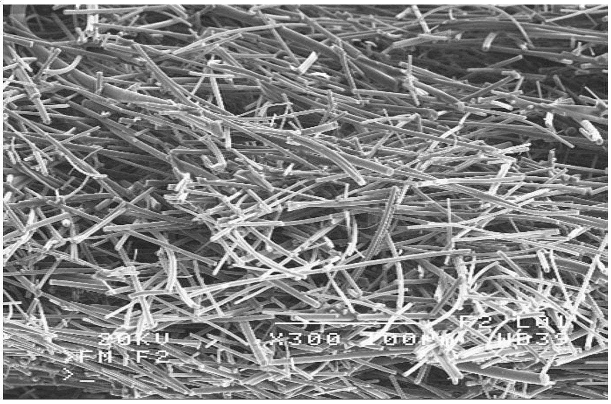

Figure 4. **Internal construction of a moulder from disordered fibres**

Slika 4. **Interna konstrukcija kalupa s neuredno raspoređenim vlaknima**

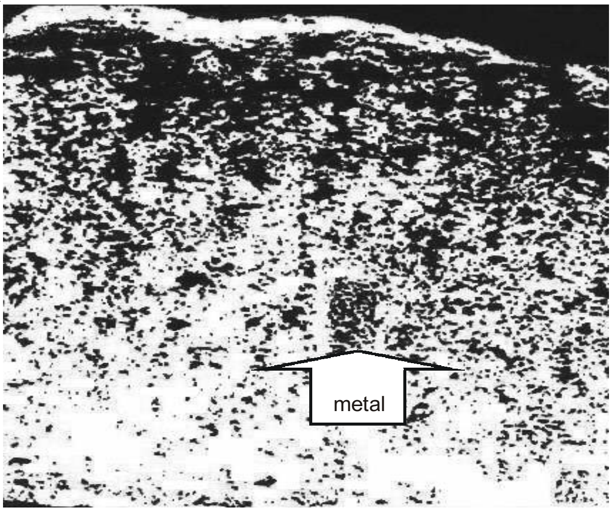

Figure 5. **Method of filling with metal the reinforcing moulder of disordered fibres (bright fields -metal matrix, dark fields - unfilled places)**

Slika 5. **Metoda punjenja kojom se ojačan kalup s neuredno raspoređenim vlaknima puni metalom (svijetla polja - metalna matrica, tamna polja - neispunjena mjesta)**

The value of capillary pressure for this case can be determined on the basis of the Young-Laplace equation, presented by formula (2), taking into consideration the linear dimension *d* instead of radius *r* and decreasing the value of angle θ by angle α/2. The equation will assume the shape [8]:

$$p_{kap} = \frac{2\sigma}{d} \cdot \cos\left(\theta - \frac{\alpha}{2}\right) \tag{7}$$

Thus, in the case when there is no wetting with liquid metal of the ceramic surface in capillaries formed in the reinforcing moulders built of disordered fibres, with numerous places of mutual fibre contact, we have to do with spaces whose complete filling with liquid metal requires high pressure values, theoretically aiming at infinity. Thus, it is impossible to attain a complete filling of the inter-fibre space and each infiltrated composite with reinforcement made of disordered fibres is porous. The application of pressure higher than necessary for the required (incomplete) filling of the capillaries is undesirable.

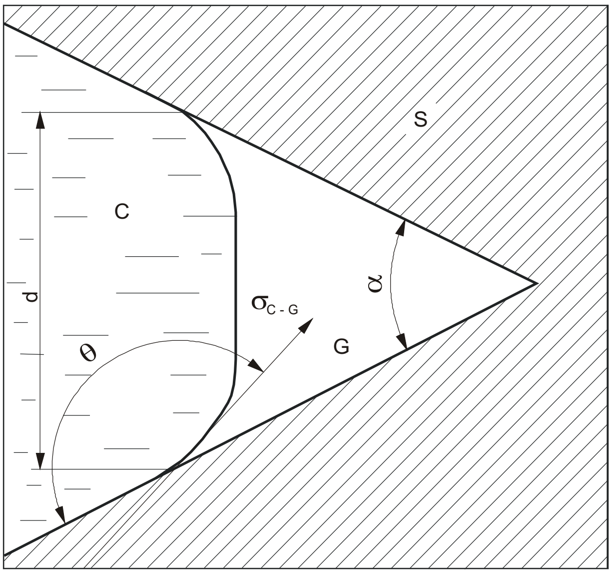

Figure 6. **Reaction of liquid in a wedge-shaped capillary of apex angle α (wetting angle $\theta > 90°$)**
Slika 6. **Reakcija tekućine u kapilari klinastog oblika s vršnim kutom α (kut vlaženja $\theta > 90°$)**

For the infiltration of any porous reinforcement with liquid metal it is necessary to fulfil the condition described by formula (1), which determines the value of the indispensable external pressure enforcing infiltration. In the process of pressure infiltration of capillaries, the value of hydrostatic pressure can be passed over in most cases, similarly to p_g and Δp for reinforcement of high porosity (about 85 %).

Assuming that the filling of reinforcement capillaries takes place in conditions that ensure the liquidity of matrix metal, it can be accepted that the infiltration pressure is equal to the capillary pressure defined by dependence (7).

The infiltration of the composite reinforcement does not take place immediately on applying particular pressure. The system attains a state of required infiltration after certain time, which can be determined experimentally. It is therefore purposeful to determine, by means of a suitable testing liquid, the dependence $\rho = f(p)$ and $\rho = f(\tau)$, as also $\rho = f(p, \tau)$. The last mentioned dependence has been called reinforcement characteristic. It allows drawing conclusions about the behaviour of the system: tested reinforcement - testing liquid. These dependences can be next applied to the system: tested reinforcement - other infiltrating metal (technical alloy).

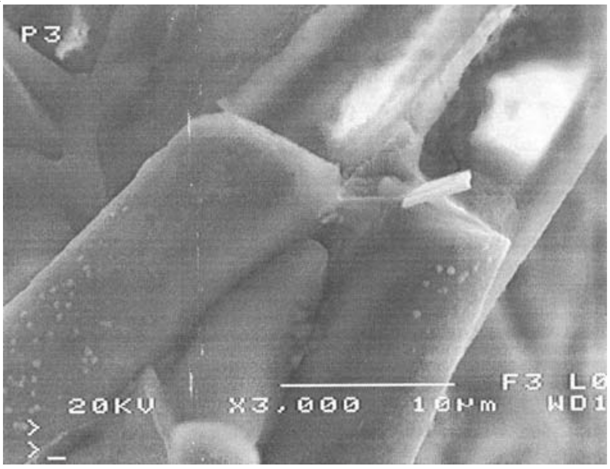

Figure 7. **Unfilled capillary space between two fibres laid in an angle**
Slika 7. **Neispunjen kapilarni prostor između dva vlakna položena pod izvjesnim kutom**

Assuming density ρ, as the criterion for assessing the degree of filling the reinforcement capillary with liquid metal matrix, we can assess the values of pressure and time necessary to obtain composite material of the right degree of infiltration (density) for a selected matrix material, with known values σ and θ, characterising the composite systems: the testing and the technical one.

The value of the pressure indispensable to make a composite cast of assumed degree of filling capillary spaces formed by contingent fibres (assumed density of composite material ρ_k) can be determined on the basis of dependences [9]:

$$p_k = \frac{p_{k\max} \cdot \tau_{k\max}}{\tau_k \cdot (1-\beta)\rho_{k\max}} \left(\rho_k - \beta \cdot \rho_{k\max}\right) \tag{8}$$

$$p_{k\max} = p_{\max} \frac{\sigma_k \cdot \cos\theta_k}{\sigma \cdot \cos\theta} \tag{9}$$

$$\tau_{k\max} = \tau_{\max} \frac{\mu_k \cdot p_{\max}}{\mu \cdot p_{k\max}} \tag{10}$$

where:

μ_k - dynamic viscosity of the liquid composite matrix,
μ - dynamic viscosity of the testing matrix,
$p_{\max}$ - pressure for the maximum density of the testing matrix composite,

τ_{max} - time for the maximum density of the testing matrix composite,
τ_k - time of infiltrating the composite,
β - density accretion coefficient,
ρ_k - assumed composite density,
$\rho_{k max}$ - theoretic composite density,
σ - surface tension of testing matrix,
σ_k - surface tension of composite matrix,
θ - wetting angle of the reinforcement material with testing matrix,
θ_k - wetting angle of the reinforcement material with composite matrix.

CONCLUSION

The method of determining the parameters of the process of infiltrating cast matrix-metal composites with reinforced fibre varies depending on the reinforcement type applied. For reinforcement from long disordered fibres arranged in a parallel way determining these parameters can be based on a mathematical record of the reinforcement geometry. For reinforcement made of short disordered fibres, on the other hand, impossible to be described geometrically, the method of determining infiltration parameters is based on the technological characteristic of the reinforcement determined by the testing liquid. This characteristic permits to determine the parameters of infiltrating this reinforcement with a selected metal as the composite matrix.

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