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Relationships between the reinforcement properties and the crystallization of MMc

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Abstract

Occurrence of a reinforcing phase in a cooling composite casting causes that its crystallization goes differently as compared to the casting without reinforcing (of traditional design). This affects the forming process of the composite structure since the moment of mixing of the components until total solidification of the composite matrix. The present paper aims at presenting several problems related to crystallization of composite castings (particle reinforced and with saturated reinforcement) that have been the subjects of the research work performed by the team of the Foundry Section of the Poznań University of Technology. The review displays the spheres of the technology of composite casting materials that are well known and the ones that require more detailed research.

Keywords: Composite castings, Reinforcement phase, Crystallization

1. Introduction

Crystallization of a suspension composite or the one with saturated reinforcement converts itself to crystallization of its matrix under the conditions of multi-component and multi-phase liquid-solid structure. Hence, occurrence of a solid reinforcing phase before initiation of the crystallization process must be conducive to differences in the course of the process as compared to crystallization of an aluminum alloy without a solid reinforcement. Former works related to crystallization of the composite castings were focused on modeling the matrix solidification process, first of all in the case of the suspension composites, with consideration of thermal effect of the solid reinforcing particles [1,2]. The thermal role of the saturated reinforcement is mentioned too by J. Grabian [3], while J. Jackowski underlines significance of the reinforcement effect on casting porosity [4] and the meaning of nucleation of primary silicon crystals [5].

The goal of the present paper is to present the role of reinforcement for the process of crystallization of the castings made of composites reinforced with particles and the ones provided with saturated reinforcement, on the grounds of the research carried out in Foundry Section of the Poznan University of Technology on the composites with Al-Si matrix. The research included:

- the role of reinforcement for the choice of technological conditions, with particular emphasis laid on the temperature of casting of particle-reinforced composites and the composites with saturated reinforcement;
- the effect of reinforcement on nucleation of the matrix crystals;
- the effect of reinforcement on the form of porosity of a composite casting.

2. The role of reinforcement for the choice of temperature of composite manufacturing

While manufacturing the composite suspension the reinforcement and matrix temperatures equalize. Value of the temperature may be arbitrarily adjusted as the suspension is made in a furnace. Only the thermophysical properties of the solidifying system are subject to changes in result of their different values in particular composite components. This results in variation of flowing ability in the mold.

The case of the composites with saturated reinforcement is different. Here the reinforcement and matrix temperatures equalize during the saturation process. The reinforcement pores are filled beginning from the ones of the largest cross-section and ending on the smallest ones. This process undergoes in the entire casting volume that is shown in Fig. 1.

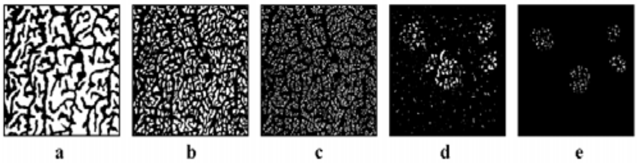


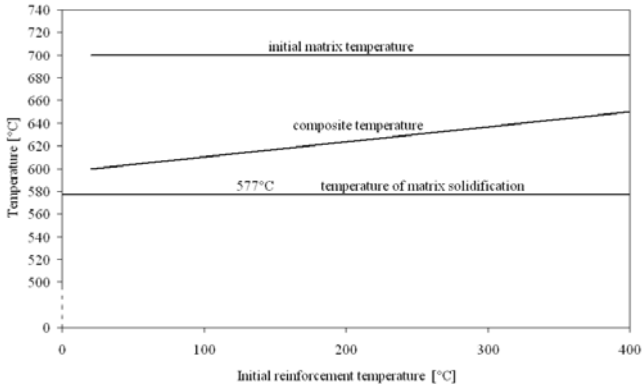
Fig. 1. A scheme of behaviour of a liquid composite matrix saturating the reinforcement – successive stages of reinforcement saturation [4]

J. Grabian [3] assumed that, due to small cross-section area of the reinforcement elements, the reinforcement and matrix temperatures equalize in shorter time than is required for achieving the liquidus temperature. Consequently, for a composite made of a pressed alumino-silicate fiber SIBRAL - Wood Alloy or – AlSi11 alloy he computed and experimentally proved that the initial matrix temperature during saturation may be determined from the thermal balance:

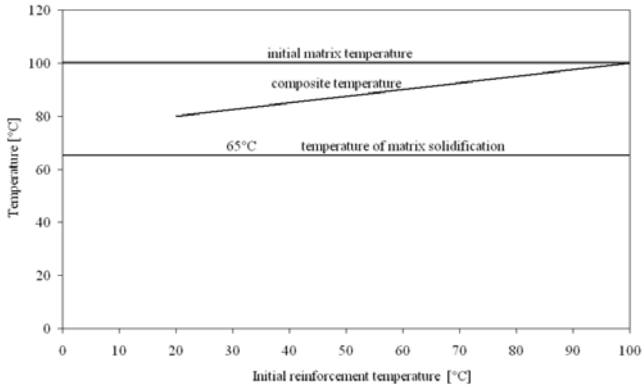
$$V \cdot P \cdot c_{met} \cdot \rho_{met} \cdot \Delta T_{met} = V(100 - P)c_{zbr} \cdot \rho_{zbr} \cdot \Delta T_{zbr}$$

where:
V – composite volume [m^3];
P – porosity of the composite reinforcement [%];
c_{met} – specific heat of the metallic saturating matrix [kJ/kgK];
c_{zbr} – specific heat of the reinforcing material [kJ/kgK];
ρ_{met} – density of the metallic saturating matrix [kg/m^3];
ρ_{zbr} – reinforcement density [kg/m^3];
ΔT_{met} – drop of the liquid matrix temperature [K];
ΔT_{zbr} – increase in the reinforcement material temperature [K]

Fig. 2. [3] presents dependence of the composite temperature in the time of equalizing the reinforcement and matrix temperatures on the initial reinforcement temperature.



a)



b)

Fig. 2. The composite temperature in the time of equalizing the reinforcement and matrix temperatures as a function of initial reinforcement temperature in case of the composites: (a) – SIBRAL – AlSi11; (b) SIBRAL – Wood's Alloy [3]

This allows to state that the considered composites may be produced by saturation even at initial reinforcement temperature equal to the environment temperature.

More accurate and reliable data might be obtained, of course, with the method of simulation of liquid metal flow through the reinforcement channels of decreasing cross-section, with the assumption that the metal in the stream front is not exchanged while its temperature decreases until the flow stops. Nevertheless, as the problem is difficult, no solution has been attempted. At least the authors do not know such an attempt.

3. The effect of reinforcement on matrix crystals nucleation

Nucleation of crystals during solidification of aluminum and its alloys is of heterogeneous character. According to Fig. 3. this process occurs at a plane and smooth surface when the nucleation angle $\theta_2 < 90º$.

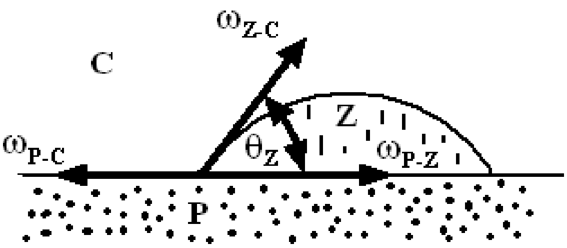


Fig. 3. Heterogeneous nucleation

Nevertheless, according to Oostdijk's opinion extensive heterogeneous nucleation occurs for the nucleation angle $\theta_2<120^\circ$ [7], due to inequalities and the fact that the surface is not perfectly plane. Values of the angle for the phases of the Al-Si alloy and other typical composite reinforcement materials with the matrix of aluminum or its alloys are specified in Table 1. The values give evidence that:

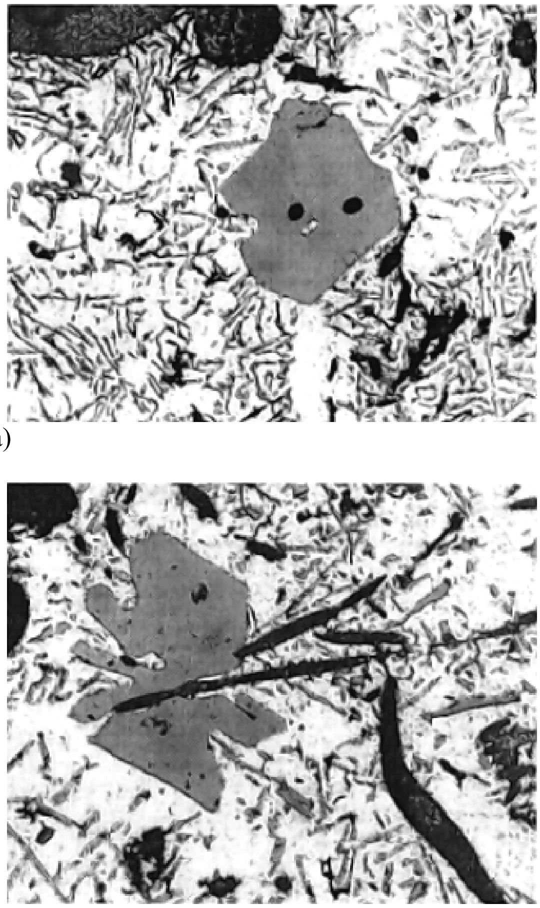
- aluminum may nucleate on the silicon grains, the inverse process being impossible;
- silicon nucleation on typical reinforcement materials of aluminum composites, like Al2O3, SiC, and coal may occur with high intensity, due to the value of the nucleation angle;
- aluminum nucleation on such bases being theoretically possible is rather unlikely.

The above findings provide confirmation to the observation of composite structures of AlSi11 Alloy matrix reinforced with an unarranged alumino-silicate (Fig. 4) and carbon (Fig. 5) fibres. The pictures show primary silicon crystals excreted on the reinforcement fibres in result of unbalanced crystallization conditions. In order to confirm correct identification microanalysis of the phases occurring in Fig. 5 has been carried out. The results are shown in Fig. 6.

Table 1.
Al and Si nucleation conditions on various bases in a liquid AlSi11 alloy [7,8,9]

Item No	Phase		ω[mN/m]			θ_Z[°]
	Base	Nucleus	$\omega_{P\text{-}C}$	$\omega_{P\text{-}Z}$	$\omega_{Z\text{-}C}$	
1.	Si	Al	1000	950	182	73,5
2.	Al	Si	182	950	1000	140,5
3.	Al_2O_3	Al	1605	1592	182	86,0
4.		Si	1605	770	1000	33,4
5.	SiC*	Al	no data		182	
6.		Si	no data		1000	
7.	C	Al	4845	4857	182	93,7
8.		Si	4845	3468	1000	0

* based on partial data it was assumed that $\theta_{Z(Si-SiC)} < \theta_{Z(Al-Al_2O_3)}$



a)

b)

Fig. 4. Primary Si crystals on the alumino-silicate reinforcement crystals: cross section (1) and longitudinal section (b), magn. 250x 1% HF [7]

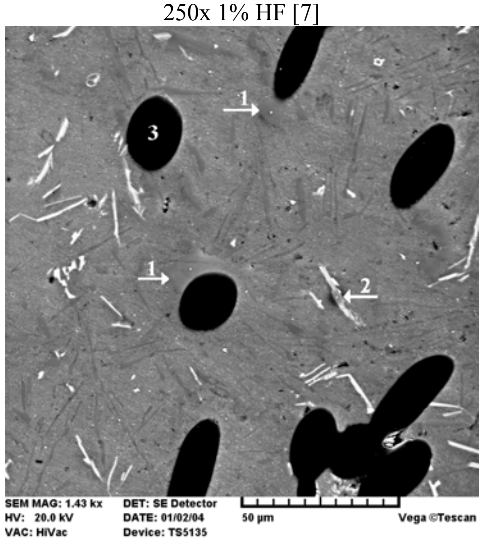
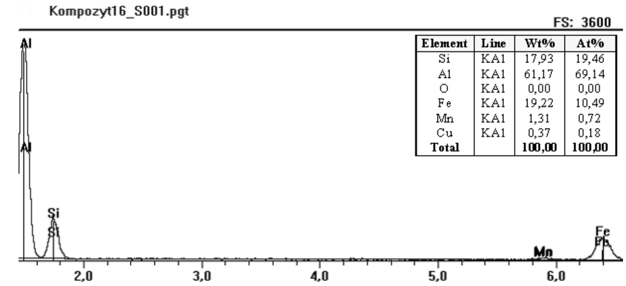


Fig. 5. Primary silicon crystal (1) on the carbon reinforcement fibres [8]



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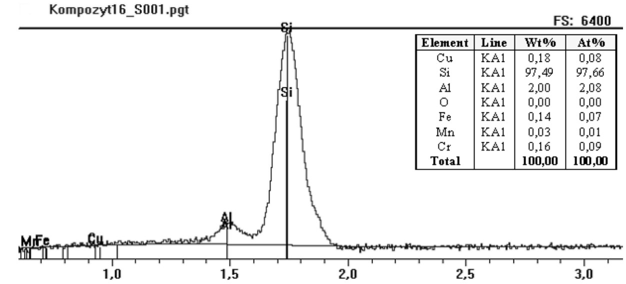

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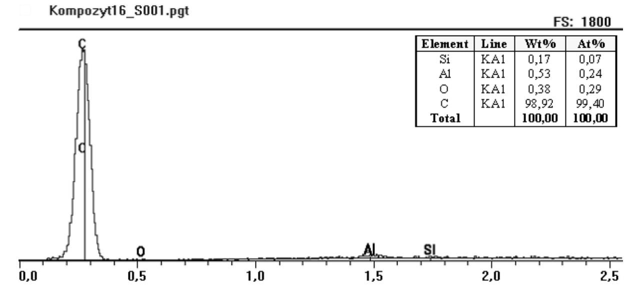
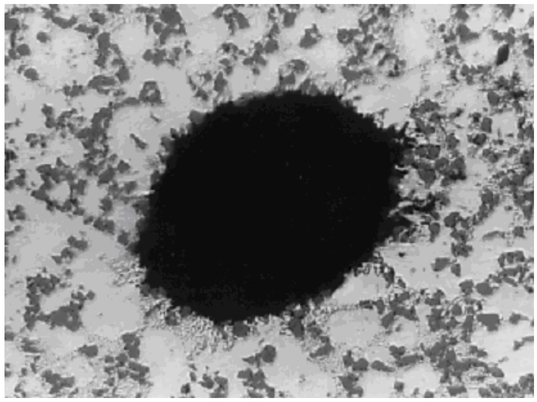


3

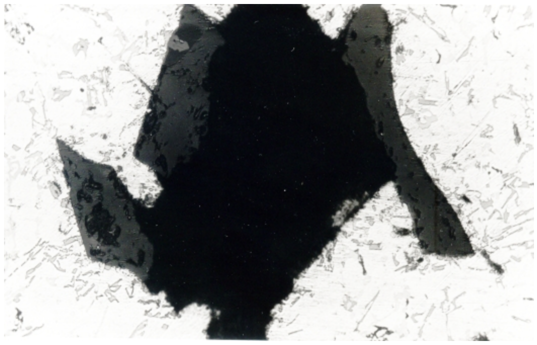
Fig. 6. Conditions of phase microanalysis based on the photography shown in Fig. 5. (the denotations 1, 2, 3 are compatible in both figures)

4. The effect of reinforcement on the form of composite casting porosity

The experiences give evidence that the composite casting with no porosity is unavailable. One of the reasons for this is occurrence of the reinforcement and its connection with the matrix. In the case of production of particle-reinforced composite castings introduction of the reinforcing phase to the liquid matrix is accompanied by creation of agglomerates [6,9,10] composed of concentrations of the reinforcing particles focused around the gas bubbles. They are stable and worsen the structure of the composite suspension and the quality of the material obtained this way. Vacuum processing of the composite suspension before casting significantly reduce porosity of the material without eliminating it totally [11]. Particular case of composite suspension casting with the use of pressure (e.g. the squeeze casting method) minimizes volume of the gaseous phase existing in the agglomerates, without eliminating it too. Fig. 7 shows the examples of the agglomerates existing in the structures of particle-reinforced composite castings.



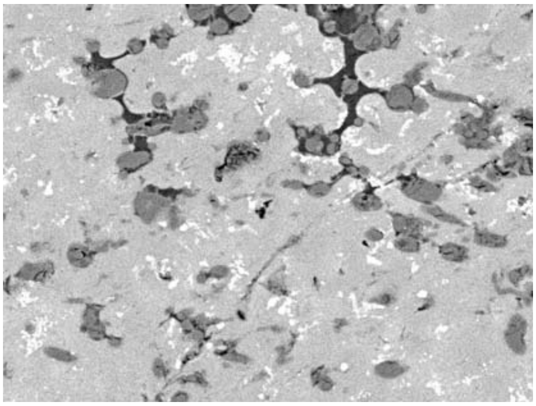
a)



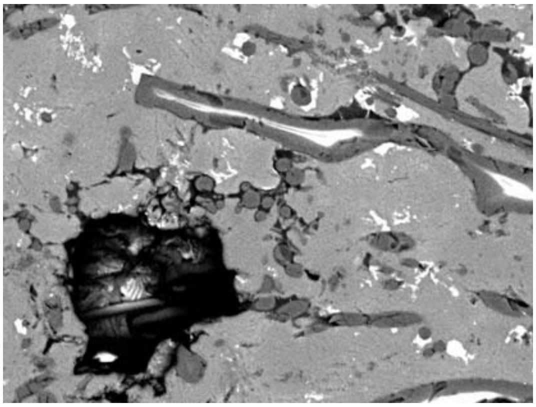
b)

Fig. 7. Example of agglomerates of the reinforcement particles around the bubbles

In case of manufacturing the suspended reinforcement composites creation of gaseous occlusions in the composite material that is formed according to the scheme shown in Fig. 1 is unavoidable [4, 12]. Their magnitude (i.e. volume) may be quite small but only in the case when the high value of the assumed pressure of the reinforcing cast profile effectively reaches each of the occlusions until the composite matrix fully solidifies [4]. Failure of this condition is conducive to the growth of the occlusions due to their decompression and the growth of composite material porosity. This is the case in so-called insulated zones, i.e. insufficiently supplied areas of the composite casting under the formation process, in which the growth of the volume of the compressed occlusion occurs at the expense of the drop of the cooling and solidifying matrix material. Strongly coupled occlusions of the composite casting structure with saturated reinforcement are shown in the Picture (a) of Fig. 8. A similarly large occlusion bearing clear signs of decompression is shown in picture (b) of the same figure.



a)



b)

Fig. 8. A compressed occlusion (a) and the one bearing the signs of decompression (b) in the structure of a composite casting with saturated reinforcement

The time required for introducing a reinforcing phase to the suspension and its homogenization is conducive to the fact that temperature of the components since the beginning of the casting process are equal. Moreover, thermophysical properties of the components making the composite suspension [13] allow to conclude that in the time of suspension casting the reinforcing phase of the cooling system should not be considered as a set of mini-chills but rather as a set of heat mini-accumulators.
Occurrence of the solid phase in the composite suspension of the temperature of full liquidity of the composite matrix metal causes that the process of supplying the composite castings should be analyzed more accurately than in the case of the castings made of traditional materials. A distinct drop in castability with growing share of the reinforcing phase in the casted suspensions [14] suggests an effect exerted on the gradient criteria of self-supplying. This in turn affects the form of shrinkage porosity in the composite castings. According to the authors the problem requires more discerning experimental research.

Table 2.
Specification of averaged thermophysical properties of the composite components, according to [13]

Component	Mass density ρ	Specific heat c_p	Heat of crystallization L	Thermal conductivity λ	Thermal diffusivity a	Heat accumulation b
	kg/m^3	kJ/kgK	kJ/kg	W/mK	$10^{-6}m^2/s$	$10^3Ws^{0,5}/m^2K$
SiO_2	2 300	1,04	-	1.6	0,67	1,96
Al_2O_3	3 900	1,07	-	3.7	0,89	3,93
SiC	2 900	1,03	-	16.5	5,52	7,02
AlSi11	2 500	1,19	389	130,0	0,53	178,87

5. Conclusion

The above presented abbreviated consideration indicated the fact that the problems related to solidification of the castings of metal matrix composites are of highly versatile character. In spite of the interest they evoke in many scientific centres the topic requires further extensive research.

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