MODELLING OF NON-METALLIC PARTICLES MOTION PROCESS IN FOUNDRY ALLOYS

The behaviour of non-metallic particles in the selected composites was analysed, in the current study. The calculations of particles floating in liquids differing in viscosity were performed. Simulations based on the Stokes equation were made for spherical SiC particles and additionally the particle size influence on Reynolds number was analysed. The movement of the particles in the liquid metal matrix is strictly connected with the agglomerate formation problem. Some of collisions between non-metallic particles lead to a permanent connection between them. Creation of the two spherical particles and a metallic phase system generates the adhesion force. It was found that the adhesion force mainly depends on the surface tension of the liquid alloy and radius of non-metallic particles.

Key words: zinc alloys, aluminium, foundry, metal matrix composites (MMC), SiC particles

INTRODUCTION

Composites based on metal matrices are used in several fields: building, aircraft industry, for products of everyday use and for sports equipment. Designing metal matrix composite (MMCs) alloys provides a wide spectrum of possibilities of obtaining materials characterised by high mechanical properties and thermal resistance. Designing new materials is much more effective when aided with computer modelling and simulation [1-10]. Among these composites the special group constitute materials based on the Zn-Al alloys matrix. Traditional Zn-Al alloys are characterised by a high abrasion resistance and good dumping properties [11-13]. Due to that, bearings and devices operating at high temperature and mechanical loads are produced from them. Constantly growing requirements concerning non-ferrous metal alloys allowed to develop advanced materials based on the Zn-Al matrix, strengthened by ceramic particles and the so-called hybrid composites [14]. The alloy strengthening by introduction of ceramic particles improves mechanical properties by increasing strength, hardness and abrasion resistance, however worsens machining properties and thermal conductivities of these materials. In extreme cases an introduction of non-metallic phase into an alloy can have negative effects causing weakening of mechanical properties. Agglomeration effects and floating out of non-metallic particles from a liquid alloy, which changes their placement in the cast composite, are reasons of this weakening. Several factors influencing the behaviour of particles is here important: a method of introducing a non-

metallic phase into an alloy, mixing, alloy viscosity, process temperature, wettability of particles by liquid metal, reactivity of ceramic particles with a matrix, formation of intermetallic phases and interactions of particles with the crystallisation front. Especially important is the technique of the ceramic particles introduction into an alloy. Not properly selected method can cause casting defects (porosity) or can contribute to undesired differences in a particle content in individual parts of the cast composite. In such cases, inhomogeneity causes structure weakening and the composite properties do not meet the expected requirements [15-23]. The present study deals with the analysis of the SiC particles behaviour in composites based on typical foundry Zn-Al alloys. Investigations concerned two types of composites: $ZnAl8/SiC_p$ and $ZnAl27/SiC_p$, differing in an aluminium content in the metallic matrix.

ADHESION EFFECT OF THE SiC PARTICLES

One of the main aims of the MMCs production technology is obtaining homogeneous distribution of particles in the alloy matrix. The SiC clusters formation is the main reason of heterogeneity of composites. Clusters can be formed due to chemical bonds between particles, decreasing the surface energy, segregation and effects related to particles floating and interactions with the crystallisation front. A formation of chemical bonds between the SiC particles is the result of introducing previously warmed silicon carbide particles into an alloy [16].

An adhesion occurs as a result of capillary forces influence, which is caused by a weak wettability of the SiC particles by a liquid alloy. This effect concerns the SiC particles being in motion, which due to their collisions form stable bonds. An occurrence of large SiC agglomerations is an unfavourable effect. Particle clusters

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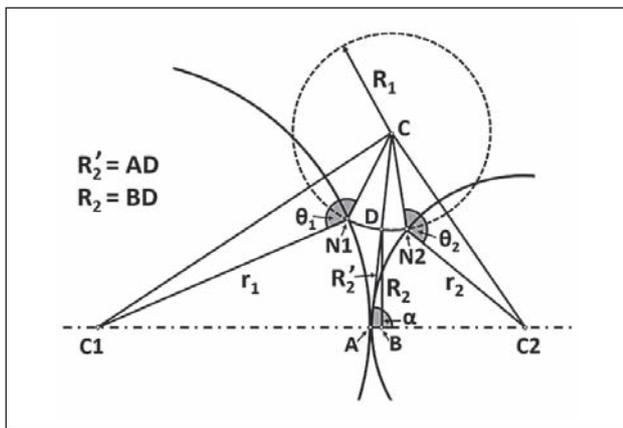
Figure 1 Schematic presentation of two spherical SiC particles forming the stable bond [24]

weaken the composite structure and act as the cracks of metal matrix. The system of two spherical SiC particles, forming stable bond is presented in Figure 1 [24].

In the vicinity of two contacting particles a ring of gases (metal vapours, dissolved gases) of a lens shape is formed. Radiuses R_1 and R_2 concern this gaseous ring. Their values depend on the wetting angle θ of a particle by an alloy. With an increase of the wetting angle the adhesion work decreases, which is considered as a wettability decrease. It is considered that the wettability is low when angles θ exceed 90° [26]. The system of two spherical particles together with the nearest surroundings cause the creation of the adhesion force between particles, which can be expressed by the dependence:

$$F_{adh} = \pi \cdot R_2{}^2 \cdot \Delta P_m + 2\pi \cdot R_2 \cdot \sigma_m \qquad (1)$$

where σ_m is alloy-particle interfacial energy.

The adhesion force is the sum of two segments. The first one corresponds to the influence of the pressure difference between a ring of gases and a liquid alloy [24-27].

$$\Delta P_m = \sigma_m \cdot \left(1/R_1 - 1/R_2 \right) \qquad (2)$$

This pressure is counterbalanced by the liquid metal pressure, which is the sum of hydrostatic and atmospheric pressures:

$$\Delta P_m = \rho\, g\, H_m + P_{atm} \qquad (3)$$

The second segment of the equation (1) takes into account the wetting angles of both particles by a liquid metal and results from the balance of surface forces.

$$F_{adh} = \pi \cdot \sigma_m \cdot \left[R_2^2 \cdot \left(\frac{1}{R_1} - \frac{1}{R_2} \right) + 2 \cdot R_2 \right] \qquad (4)$$

θ$_1$ and θ$_2$ – wetting angles between particles and a liquid alloy, R_1 – radius of curvature of a liquid alloy in the neck area, α – angle between R$_2'$ and a line joining particle centers.

It results from the equation, that the adhesion force of two non-metallic particles depends on the liquid alloy surface tension. The adhesion force value corre-

sponds to the stability of bonding between ceramic particles. The adhesion effect can be limited by increasing the wettability by introducing porous ceramic particles and by lowering the alloy surface tension.

FLOATING OF THE SiC PARTICLES

The SiC particles being in a liquid alloy are floating in accordance with the Stokes law [17]. In case of spherical precipitates, which sizes do not exceed 100 /μm, being in a moderately mixed steel (Reynolds number – Re < 1), their floating velocity can be calculated from the equation:

$$v = \frac{2}{9} g\, r^2 \frac{\left(\rho_m - \rho_p \right)}{\eta} \qquad (5)$$

$$\mathrm{Re} = \frac{2\, g\, r^2\, v}{\eta} \qquad (6)$$

where: v – floating velocity/ m s^{-1}, g – acceleration of gravity/m s^{-2}, ρ_m and ρ_p – alloy and SiC particle density/ kg m^{-3}, η – dynamic viscosity of alloy/Pa·s, r – radius of floating precipitate/m.

Calculations of floating velocity and Re were performed for the SiC particles of a radius: 0,000001 - 0,0001/m, ρ_m = 6 569/kg m^{-3} for ZnAl8/SiCp, ρ_m = 4 754/kg m^{-3} for ZnAl27/SiCp, η = 0,0177/Pa·s ZnAl8/SiCp, η = 0,0128/Pa·s ZnAl27/SiCp – Figures 2, 3.

Precipitate size is not always spherical. Eq. (1) can be applied for precipitates, which are not deformed during floating. Investigations of Popiel and Dieriabin [25] indicated that particles of the same density and of shapes differing from spherical are floating 25 - 30 % slower, than spherical particles.

An application of mechanical mixing during introduction of the SiC particles into the alloy matrix causes rotational motion and particles gathering in the crucible axis zone. The force acting on the SiC particles can be determined from the dependence [18]:

$$F_r = x \cdot \varpi^2 \cdot \left(\rho_m - \rho_p \right) \qquad (7)$$

where: x – distance of the precipitated particle from the crystalliser axis/m, v - angular rotational speed.
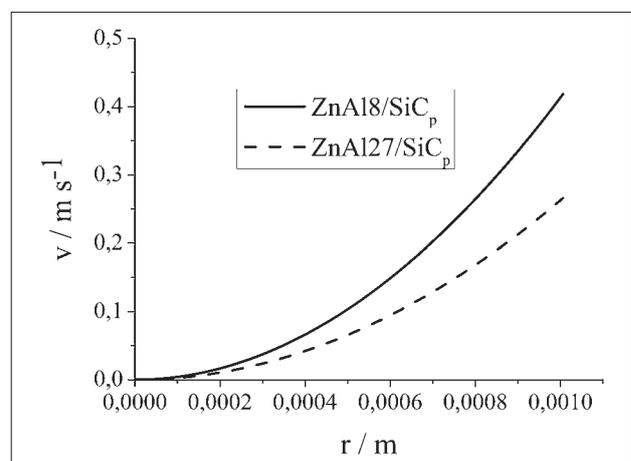

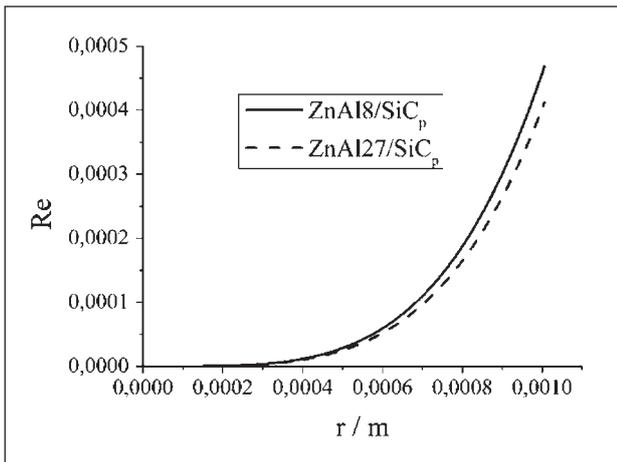**Figure 2** SiC particles floating velocity v as a function of the particle radius r

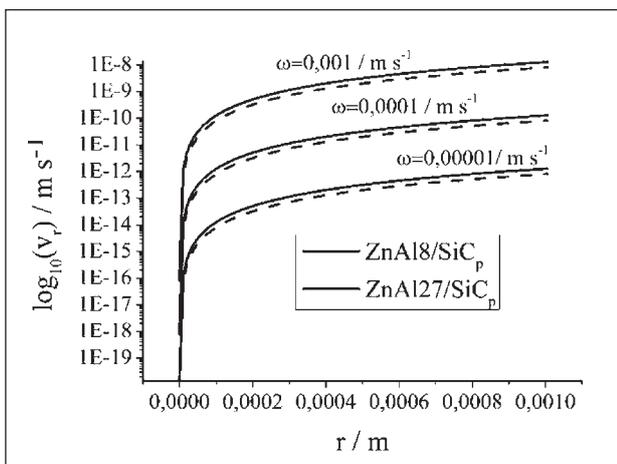**Figure 3** Reynolds number as a function of floating particle radius r

Figure 4 SiC particles moving velocity in the crucible axis direction v_r as the function of rotational speed ω and the particle radius r

The maximal velocity with which the SiC particles are moving in the axis direction, results from the above.

$$V_r = \frac{2 \cdot (\rho_m - \rho_p) \cdot r^2 \cdot \varpi^2 \cdot x}{9 \cdot \eta} \qquad (8)$$

Calculations of the moving velocity of particles in the axis direction were performed for particles being at a distance of $x = 0,5/m$ at the rotational speed ω = 10^{-5} – 10^{-2}/m s^{-1}.

EXPERIMENTAL TESTS

The ZnAl8 (binary alloy made of 99,99 % Zn and 99,99 % Al) composite containing the SiC particles in amount of 5 vol % and of particles mean diameter 500 μm, was used in tests. Liquid alloy was melted at a temperature of 500 °C, and then SiC particles were introduced into it. The composite was prepared by mechanical mixing. This material was applied for making rectangular (plates) castings of dimensions 20 x 100 x 130 mm. After hardening the samples for making metallographic microsections were taken. Samples were cut-out in perpendicular plane passing through the plate centre. Some examples of tests are presented in Figure 4.
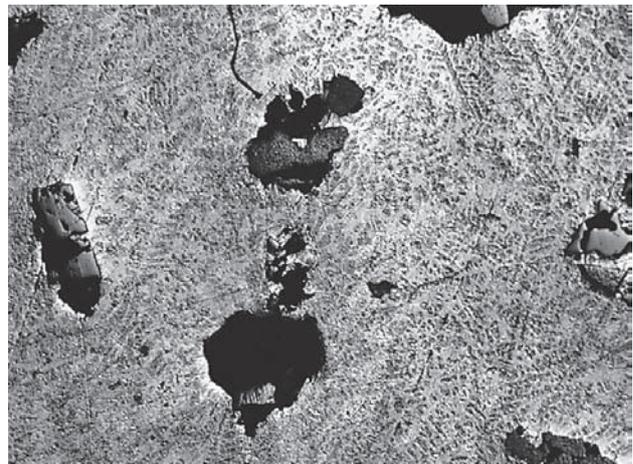

Figure 5 Microstructure of the ZnAl8/SiC$_p$ composite from the sample taken from the upper part of the plate

When the mould is being filled with a mixture of a liquid alloy and ceramic particles there is a danger of separating these components - due to large differences in their densities - despite their uniform distribution before pouring to the mould. An essential factor constitutes the amount of non-metallic phase introduced into an alloy. Its increase will cause a heterogeneous distribution in the matrix being the result of worsened wetting conditions of particles by an alloy and an increased matrix viscosity (see also Figure 5).

CONCLUSIONS

The analysis of the SiC particles behaviour in liquid zinc alloys indicated that this behaviour depends on: wetting angle in a particle-matrix system, particle sizes, amount and their surface state. Surface effects decide on the adhesion force of the individual SiC particles and on the aggregates forming. The surface tension and viscosity of a liquid alloy are parameters deciding on the adhesion force. The effect of ceramic particles floating and gathering in the upper part of the plate is the result of a weak wetting of particles by a liquid alloy, too high process temperature and large density differences between the metal-matrix and solid particles. The additional parameter constitutes the rotational motion (due to a mechanical mixing), which facilitates lifting ceramic particles to the surface and favours their gathering in larger agglomerates.

Acknowledgements

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