# **Processing of MMC Reinforced with Small-size Particles**

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## Abstract

This paper discusses the development of new methods of producing metal matrix composites (MMC). As theoretical estimates show that it is not preferable to use liquid phase methods for producing MMC with reinforcing particles of less than  $1\mu$ m, the focus was on the development of MMC production methods without liquid-phase formation. Two methods were developed: a) based on nano-materials and b) based on mechanical alloying. The developed methods produce high-quality metal matrix composites with various-size reinforcing particles (including those less than 200 nm).

## 1. Theoretical Estimation of the Influence of Particle Size on MMC Processing

Nowadays industry has a demand for metal matrix composites with small-size reinforcement particles, including nano-particles [1]. There are several methods of approach to satisfy this demand [2,3]. In this research, to choose the most promising method, we investigated a theoretical correlation between the size of particles and the chemical composition of matrix body. The need to predict the properties of the final product depending on different factors results in numerous mathematical simulations and approaches of methods of production and MMC properties. For example, Kim and Rohatgi [4] studied nucleation of the Si component on ceramic particles in cast metal-matrix composites depending on temperature, volumetric fraction and chemical composition. They found that segregation of the soluble substance near the surface of reinforcement particles due to thermodynamic criterion results in changing the chemical composition of melt in the local areas (near particles).

The free energy of the solution contacting with the surface of the reinforcement particle is larger than the energy of the melt removed from it. It happens due to "particle–melt" contact surface energy, which results in the enrichment of the melt contacting with the silicon carbide particle with solute atoms, in our case, with silicon. It is possible to estimate the spacing interval  $R_2$ , within the limits of which solute atoms diffuse to the particle surface in the case of uniform distribution of reinforcing particles in the melt volume. Let us assume that the volume of the melt layer belonging to the silicon carbide particle of radius

 $R_1$ , on the one hand, is equal to  $\frac{4}{3}\pi(R_1+R_2)^3-\frac{4}{3}\pi\cdot R_1^3$  and on the other hand to

 $\frac{4}{3}\pi R_1^3 \frac{1-\varepsilon_p}{\varepsilon_p}$ , where  $\varepsilon_p$  is the volumetric fraction of reinforcing particles. Hence, it follows:

$$R_2 = R_1 \left[ \left( \frac{1}{\varepsilon_p} \right)^{1/3} - 1 \right] \,. \tag{1}$$

The difference in Gibbs free energy of the solution surrounding a particle and that away from it can be expressed as [4]:

$$G_b^p - G_b = \sigma_{pl} V_m^b / R_2 \quad , \tag{2}$$

where  $V_m^b$  is the molar volume of solute in the contact zone near the particle;  $\sigma_{pl}$  is surface energy between the particle and the solution (melt);  $G_b^p$ , Gibbs molar energy of the solute in the enriched layer;  $G_b$ , free energy of solution far from the particle.

The free energy of solute in a liquid in contact with the particle is calculated using the known formulae. Using the methods described in [4], the following formula can be obtained:

$$\frac{X_b^p}{X_b} = \exp((\sigma_{pl}^a V_m^a - \sigma_{pl}^b V_m^b) / R_2 RT) \quad . \tag{3}$$

Analysis of this formula (with the data of  $\sigma_{pl}^{a}$  and  $\sigma_{pl}^{b}$  from [4]) shows the modification of the dimensionless concentration of silicon in the enriched layer depending on the reinforcing particle size (Figure 1). The relations obtained show that the reduction of the reinforcing particle size results in a sharp increase of chemical heterogeneity of the alloy, i.e., in the significant deterioration of material properties. Figure 1 shows that with the particle size of 0.5 µm the concentration of the melt in the layer around the particle is 9% higher than that of the remaining melt. The further decrease of the size of reinforcing particles results in an even greater heterogeneity of the chemical composition of the melt. Thus, the theoretical estimation of processes of obtaining metal-matrix composites with formation of the fluid phase showed that at particle sizes less than 0.5 µm, the application of casting methods in production of metal-matrix composites results in a considerably heterogeneous distribution of alloying components in the matrix, which is undesirable, as it will result in non-uniformity of their properties.

Two new methods of producing metal-matrix composites without liquid phase formation were therefore offered. The first method is based on the use of nano-materials to obtain the matrix and the second, on mechanical alloying.



Figure 1: Dimensionless equilibrium solute concentration  $(X_b^p/X_b)$  vs size of SiC reinforcement at various temperatures: (a) 600°C, (b) 700°C, (c) 800°C.

### 2. Experimental Methods, Results and Discussion

The main idea of the first method consists in using high activity of particles in nano-scale state. Figure 2 is a TEM image of aluminum nano-particles on the surface of a silicon carbide particle. Temperature of test is lower than melting point of aluminum. No pretreatment of the surface of silicon carbide particle was used. The shapes of aluminum nano-particles as well as the value of wetting angle suggest a high wettability between aluminum and silicon carbide when nano-size aluminum powder is used. This figure helps to understand that the size of silicon carbide particles has almost no influence on the processes of their wetting by aluminum, therefore, silicon carbide particles of submicron size can be used.

To obtain Al nano-powders, the method of electrical detonation of a wire (EDW) [5], was used. The method includes preparing a mixture from Al nano-powder and SiC particles and its subsequent compacting. The mixture was prepared immediately before compaction. First, aluminum powder was disintegrated in hexane for 1 h. Then a required amount of SiC powder also disintegrated in hexane was added. This mixture was dispersed with simultaneous stirring and evaporation of hexane for 1.5 h. The creamy mass obtained was compacted by either magnetic-impulse pressurizing (MIP) or by MIP combined with explosion. The quality of the samples obtained was estimated by analyzing the structure by means of optical, scanning electron and transmission electron microscopy. The interface had no pores, inclusions, other phases or defects; there was only a dense contact between the components (Figure 4). The developed method yields a uniform distribution of reinforcing particles inside the matrix (Figure 5) and produces MMC with small-size reinforcing particles.



Figure 2: TEM image of aluminum nano-particles on the surface of a silicon carbide particle. Temperature is lower than the melting point of aluminum.

The second developed method of producing MMC is based on mechanical alloying. This method includes co-processing of matrix material particles and ceramic fragments in a planetary mill. For this work, commercial aluminum alloy Al–12.1%Si–2.2%Cu with small additions of Mg, Fe, Mn and Zn was used as matrix material; silicon carbide particles 40  $\mu$ m in size were chosen as reinforcements; mill's containers with quasi-cylindrical milling bodies were used. Powders of matrix material and reinforcements were put in mill's containers under argon atmosphere and treated for 30 up to 120 min. Shock-wearing loading led to the following structural transformations. At the beginning of treatment, silicon

carbide and matrix material particles were gradually ground (particles of SiC up to an average size of about 3  $\mu$ m; matrix material particles up to 10–250  $\mu$ m) to be of compact round shape. Simultaneously with grinding of particles, SiC fragments penetrate into viscous aluminum material and sometimes cut it. As the result, granules become finer. Basically, at the first stage, the structure of granules is not uniform. Almost each granule consists of weakly joined bits of matrix material with SiC fragments embedded into them. Compaction of granules at this stage produces material with sufficiently large, unevenly distributed SiC particles (Figure 6a).



a b Figure 3: Matrix material nano-particles penetrate into a narrow clearance (100-200 nm) between SiC particles.



Figure 4: The "matrix-reinforcement" interface.



Figure 5: Uniform distribution of reinforcing particles inside the matrix in MMC using nanomaterials.

Increasing the treatment time leads to structure development. As the result of permanent alternation of embedding ceramic fragments into matrix bits, grinding particles, joining, deforming and disintegrating granules, a layered structure starts to form. It is characterized by alteration of zones with different quantity of SiC fragments of various sizes. Further increase of the treatment time leads to a reduction of SiC reinforcing particles and their uniform distribution inside the aluminum matrix. Compaction of granules at this stage produces material with the uniform distribution of fine-size SiC reinforcing particles inside the aluminum matrix (Figure 6b).

The structure of developed material was further studied by transmission electron microscopy, which showed the "matrix–reinforcement" interface to be free of pores, cavities, inclusions or any other defects. Only dense strong contact was present (Figs. 7,8). Dynamic compaction was found to yield a fine structure of matrix with grain size of around 25–30 nm (Figure 7). In this case, average reinforcements are smaller than 1  $\mu$ m in

size and a large part of SiC particles are smaller than 200 nm (Figure 8). In all cases, the interface is free of defects.







Figure 7: Structure of MMC after dynamic compaction (TEM image).



Figure 8: Fine SiC reinforcing particle inside aluminum matrix (TEM image).

## 3. Conclusion

The developed methods produce metal matrix composites of various-size reinforcing particles (including less than 200 nm). MMC produced are characterized by a uniform distribution of reinforcements inside the matrix. There are no pores, inclusions and other defects on the interface between components.

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