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THE CORRELATION BETWEEN THE PROPERTIES AND THE TYPE OF REINFORCEMENT IN Al-MATRIX POWDER-METALLURGY COMPOSITES

KORELACIJA LASTNOSTI IN VRSTE OJAČITVE V MATIČNIH KOMPOZITIH IZDELANI PO METODI METALURGIJE PRAHU

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Al-SiC particles (Al-SiC_p) composites were fabricated by the admixture method using an Al-coated reinforcement and atomised matrix powder. The microstructure of the samples in the hot-pressed condition with the homogeneously dispersed reinforcement was monitored. The use of a coated reinforcement to make composites by powder metallurgy (PM) methods was found to yield superior mechanical properties than the use of a mixture of reinforcement and matrix powder. The coated-reinforcement sample had lower porosity, increased hardness and a higher compressive yield strength. The coating diminished direct reinforcement-reinforcement contact and promoted sintering with a resulting low porosity.

Key Words: composites, coated-reinforcement, metal matrix

Kompoziti Al-SiC (SiC_p) so bili izdelani po metodi aditivnega mešanja iz ojačitve, prekrite z aluminijem, in vodno atomiziranega prahu. Mikrostruktura je bila preiskana po vročem stiskanju zlitine z enakomerno porazdeljeno ojačitvijo. Uporaba prekrite ojačitve za izdelavo kompozita po P/M-metodi daje boljše mehanske lastnosti kot uporaba zmesi prahu ojačitve in matične kovine. Manjša je poroznost, večja je trdota in večja je tlačna meja tečenja. Prekritje je zmanjšalo kontakt med zrni ojačitve in omogočilo sintranje z majhno poroznostjo.

Ključne besede: Al-kompoziti, prekrita ojačitev, kovinska matica

1 INTRODUCTION

The incorporation of silicon-carbide particles (SiC_p) in metal-matrix composites (MMCs) results in improved wear resistance, thermal resistance, hardness, yield strength, etc. These properties increase the utility of metals, which are traditionally known for being ductile, moderately hard, having good tensile strength and moderate thermal resistance. SiC_p have found the most important application in aluminum-matrix composites. Extensive reviews of the deformation mechanisms that occur during the incorporation of fibres, particles and whiskers into the metal matrices have been presented in literature, with using of short fibres, preform infiltration, extrusion and squeeze casting [1,2]. Spray casting is a well-established technique in powder metallurgy (PM), that uses fibre reinforcement [3,4]. The use of a different reinforcement technique, the so-called "coated-reinforcement method" [5], has been used to make copper-matrix composites, as well as copper-matrix and silver-matrix composites for use as brushes. In recent years, the coated-reinforcement method has been used by the Specialty Metal Products Division of AMETEK inc. to make Cu-Mo composites. Classical methods of conventional PM that use filler and metal matrix powder have been restricted to a low filler contact with an increasing filler volume fraction. In sintering processes, the working temperature is below the melting point of the matrix, but the reinforcement usually has a higher melting point than the matrix. Because of this, excessive reinforcement-reinforcement contacts lead to a composite with inferior properties due to ineffective reinforcement-reinforcement sintering at the relatively low processing temperature (lower than that required for reinforcement-reinforcement sintering). The ineffectively sintered reinforcements constitute defects in the composite. Reinforcement-reinforcement contact leads to a higher porosity level. The flow of the softened metal matrix, could be prevented and the intersticies would not be filled during sintering.

This paper describes a solution to the problem that uses reinforcements coated with aluminum to eliminate the possibility of direct reinforcement-reinforcement contacts.

The properties of the corresponding composites made by the coated-reinforcement method and by the admixture method were compared. It was found that the composites with aluminum-film-coated SiC particles were superior (compressive strength, hardness, electrical conductivity) to the corresponding composites made by the admixture method.

2 EXPERIMENTAL

The Al-SiC_p composites containing up to 15 wt% of reinforcement were fabricated by two methods. The first

Table 1: Chemical composition of aluminum alloy (wt.%)
Tabela 1: Kemična sestava aluminijeve zlitine (mas.%)

Element	Si	Cu	Be	Fe	Mo	Ni	Co	Mg	Mn	Al
Content	11.01	1.32	0.25	0.97	0.15	0.90	0.17	1.24	0.04	Balance

Table 2: Chemical composition of SiC_p filler (wt.%)
Tabela 2: Kemična sestava polnila SiC_p (mas.%)

Element	$C_{graphite}$	Si_{metal}	TiO_2	Fe_2O_3	Al_2O_3	CaO	MgO	SiC
Content	0.12	1.88	0.14	0.50	0.14	0.13	0.04	96.65

is the Al-coated method (using SiC particles coated with a thin film of aluminum), and the second is the admixture method (based on mixing Al powder and SiC particles).

The chemical composition of the Al-Si alloy used in this study is given in **Table 1**.

The powder with a mean particle diameter (d_{50}) of 150 μm (**Figure 1**) was made by the rotating-electrode process. The SiC particles used in this experiment were made in RUSE fertilizer factory in Slovenia. The chemical composition of SiC is shown in **Table 2**.

The SiC_p was prepared by sieving six fractions: -30 μm, +30-75μm, +75-100 μm, +100-125 μm, +125-150 μm and over 150 μm. Thegranulation of -30 μm was used in the experiment. After mechanical preparation, the SiC_p was chemically treated with a concentrated HCl solution for 30 min to eliminate metallic elements.

In order to make the coated reinforcement, a thin aluminum film was deposited on the surface of the SiC_p using physical deposition. The matrix powder was kept under a vacuum of 10^{-4} Pa, then exposed to the flow of argon until the pressure reached 1Pa. The argon was ionized, the ions were accelerated by voltage of 2 kV towards the Al cathode. The aluminum ions were thrown from the cathode and deposited on the powder surface. The deposition was uniform, because the particles, so the number of particles which were not covered on the both sides was negligible.

Mixing of the coated-reinforcement and the Al-Si-matrix powder was carried out in a ball mill. All the specimens were cold pressed in a graphite die to form a cylindrical green compact of 8-mm diameter and 10.5-mm heigh. The samples were pressed in a Carver Inc. Auto "C" series automatic hydraulic press, model 388. The preform was exposed to a pressure of 153 MPa during 25 min of cold pressing, then heated together with the die for 20 min at 470 °C. The Semi-solid system was subsequently hot pressed (380 °C) in the same die, for 10 min upon the pressure of 115 MPa. For the comparison, the corresponding composites made by the admixture method were fabricated under the same processing conditions. In both cases, the filler content varied as follows: 2, 5, 10, 15 wt%. The PM route for both methods is shown in **Figure 2**.

Composite testing involved the following: density measurement, metallographic investigation, mechanical testing (compressive yield strength, compressive rupture strength, compressive deformation) and hardness testing. The microstructural characterisation was done with a scanning electron microscope SEM JEOL JSM-840. Mechanical testing was carried out on a FPZ HECKERT RAUENSTEIN 100/1 standard testing machine. Hardness testing was done with standard Brinell hardness equipment (Detroit Testing machine) HB 2.5/1000/30.

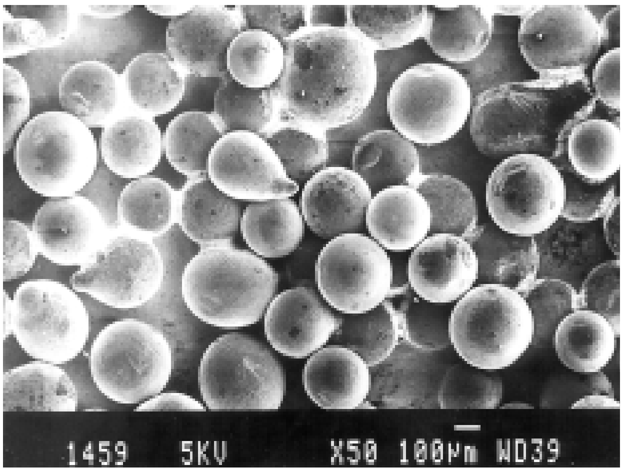

Figure 1: Scanning electron micrograph (SEM) of Al-Si powder
Slika 1: Posnetek praha Al-Si v vrstičnem elektronskem mikroskopu (SEM)

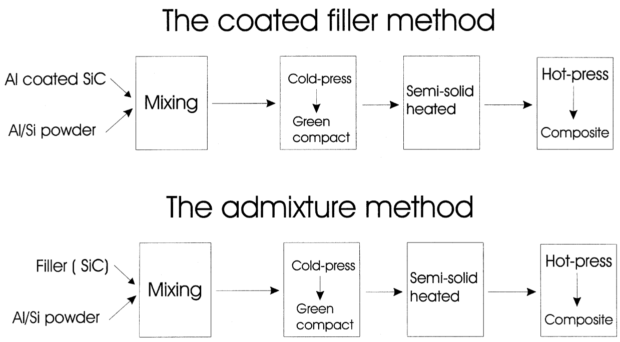

Figure 2: PM technique for coated filler and admixture methods
Slika 2: PM-tehnika za prekrito polnilo in za konsolidacijo z mešanjem

3 RESULTS

3.1 Microstructural analysis

Figure 3 shows SEM micrographs of polished sections of the Al-SiC_p composites. At the lower part of the cylindrical testing specimen the SiC particles are uniformly dispersed within the matrix (**Figure 3a**). Near the top surface of the testing cylinder SiC particles were found at the original droplet boundaries, producing cell-type microstructure (**Figure 3b**). This is attributed to the presence of excess liquid phase in the upper part of the form and the rejection of SiC particles by the solidification front[6]. Electron microscopy confirmed that, for low reinforcement contents, there is no apparent microstructural difference between the composites made by the two methods. Composites made by both methods are nearly e free of pores, with the distribution of the reinforcement depending on the specimen's height.

We found that the weight per cent of the aluminum film formed on the SiC particles, under the same deposition conditions, increased with a decrease in the SiC particle size. This is due to the larger surface area of the smaller size of SiC particles. **Figure 4** shows a micrograph of an aluminum-plated SiC particle.

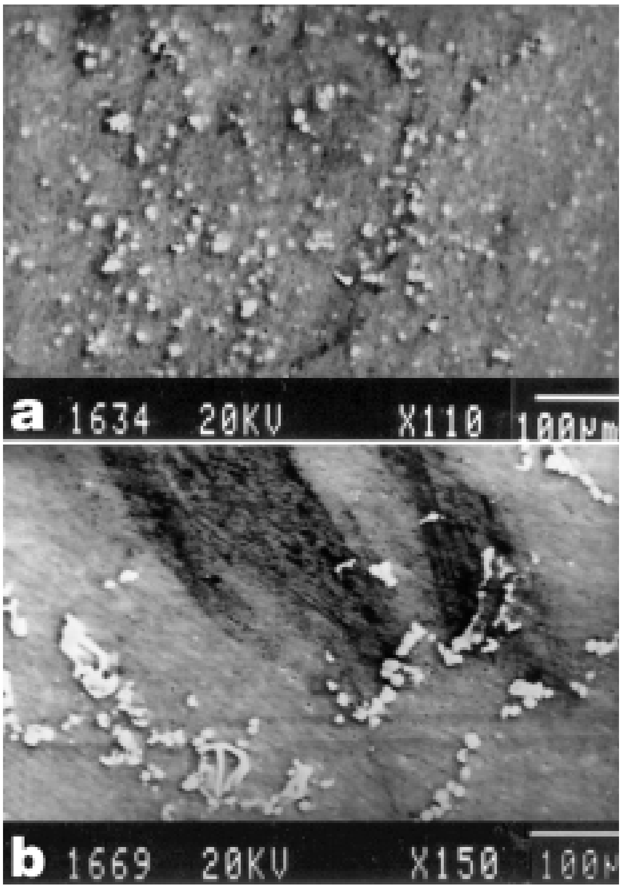

Figure 3: SEM of MMCs with 10 v/o SiC_p coated filler; a) dispersed-structure type; b) cell type
Slika 3: SEM-posnetek MMCs z 10 vol.% SiC_p prekritega polnila; a) struktura disperznega tipa; b) celična mikrostruktura

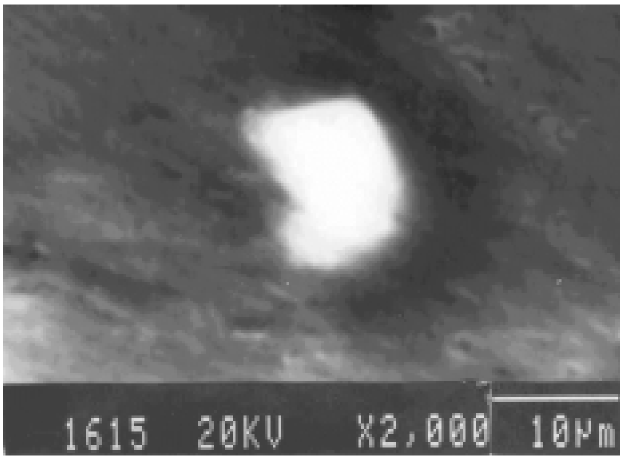

Figure 4: SEM micrograph of aluminum-plated SiC particle
Slika 4: SEM-posnetek zrn SiC, prekritih z aluminijem

The average aluminum film thickness was 2-3 μm.

A scanning electron micrograph of a metal-matrix composite after hot pressing is shown in **Figure 5**. The dark parts with irregular shapes are the pores which are located among SiC particles. During the hot pressing and pressure action the SiC particles cracked easily. This phenomenon can be observed in **Figure 5a**. The larger the particle size, the higher the possibility of cracking. **Figure 5b** reveals that there is more porosity in the composites without coatings. In the case of composites made by the admixture method, SiC particles peel off easily during the process. The peeling of particles is due to the weak interfacial bonding between the SiC_p and the matrix. It appears that the bonding is weak between the Al matrix and the noncoated reinforcement, but strong in the case of the coated reinforcement.

3.2 Physical and mechanical properties

The density of the sintered composites was measured using the buoyancy method (ASTM B328-92).

The porosity was determined by:

$$V_p=1-\rho/\rho_0 \qquad (1)$$

where: V_p is the pore volume fraction,

ρ the measured density,

ρ_0 theoretical density.

For the measurement of the electrical conductivity, standard four-probe testing was used.

Measured properties are given in **Table 3**.

Table 3 shows that the measured physical properties of the differently processed composites are almost the same for a small reinforcement content (2 wt%). In the case of composites with a higher reinforcement content the coated method appears to be supperior to the conventional admixture method.

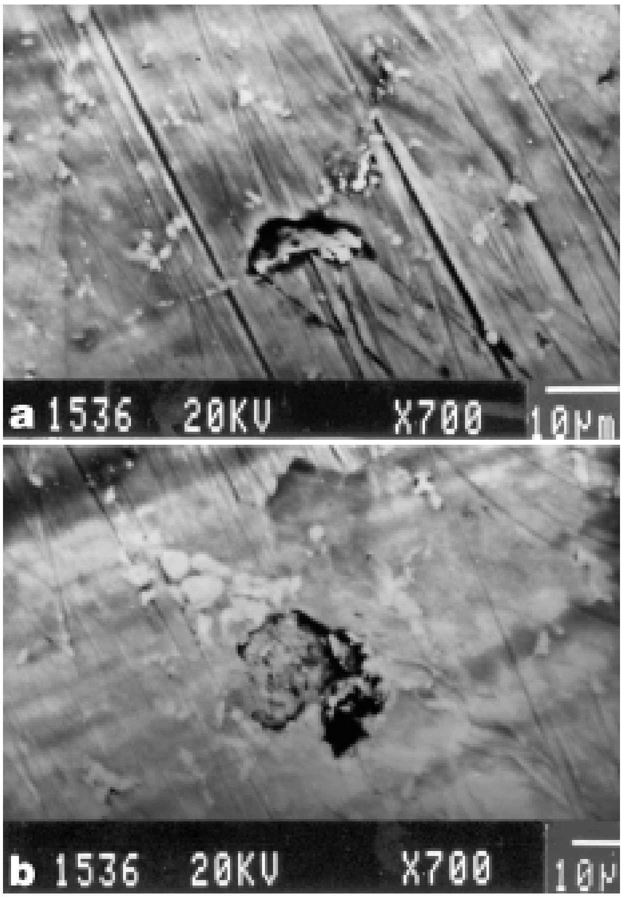

Figure 5: SEM of 15 v/o SiC matrix after hot processing; a) coated-filler compact; b) admixture-method compact
Slika 5: SEM posnetek 15 vol.% SiC matice po vročem procesiranju; a) stisnjenec s prekritim polnilom; b) stisnjenec z dodatkom polnila

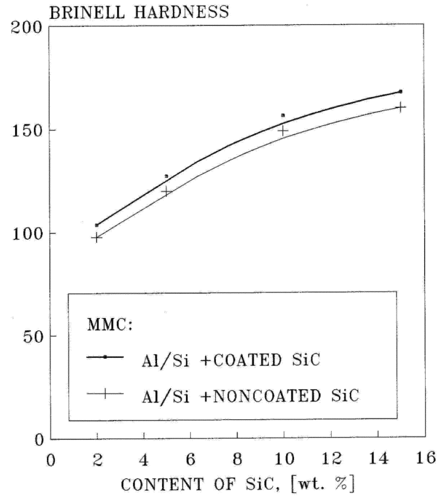

Figure 6: Influence of SiC_p content on hardness of MMCs
Slika 6: Vpliv vsebnosti SiC_p na trdoto MMCs

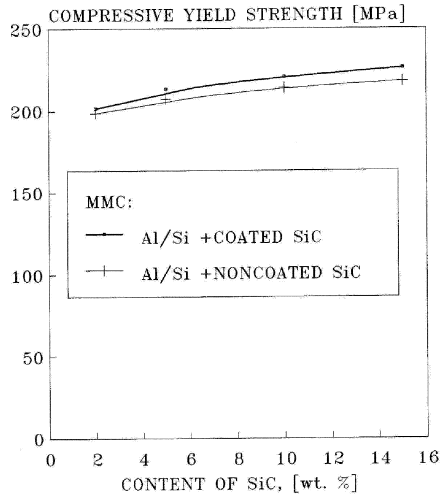

Figure 7: Influence of SiC_p content on compressive yield strength
Slika 7: Vpliv vsebnosti SiC_p na tlačno mejo tečenja

3.3 Mechanical properties

The dependence of composite hardness on the of SiC_p content is presented in **Figure 6**.

The hardness increases with increasing SiC_p content for both methods of composite preparation.

The composites produced by the coated-reinforcement method show an improvement in the hardness (up to ~5%) in the case of the higher reinforcement content.

The influence of SiC_p content on the compressive yield stress is presented in **Figure 7**. The compressive yield stress increases with increasing content of reinforcement in composites made by both methods. The use of the coated reinforcement means higher values of compressive yield stress, compared to the composites made by the admixture method.

All the specimens were compressed without fracturing, but small cracks developed on the specimen surface. Because the composites show ductile behaviour, the values for compressive strength may only bee arbitrary values, dependent on the degree of distortion

Table 3: Properties of Al-matrix composites
Tabela 3: Lastnosti kompozitov z aluminijevo matico

Composite	Al/SiC_p 2% wt. of SiC_p		Al/SiC_p 5% wt. of SiC_p		Al/SiC_p 10% wt. of SiC_p		Al/SiC_p 15% wt. of SiC_p	
Property	Admix	Coated	Admix	Coated	Admix	Coated	Admix	Coated
Porosity vol. %	0.18	0.18	0.21	0.20	0.27	0.22	0.42	0.37
El.Cond. MS/m	21.2	21.2	17.8	18.5	16.32	17.9	14.98	15.21

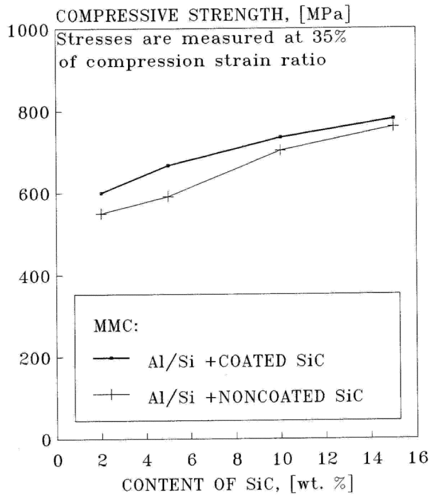

Figure 8: Influence of SiC_p content on the compressive strength at 35% of the compressive strain ratio

Slika 8: Vpliv vsebnosti SiC_p na tlačno trdnost pri tlačnem razmerju 35 %

that is regarded as effective failure for the material. The dependenceof the compressive strength at 35% of the compressive strain ratio, on the SiC_p particles content is shown in **Figure 8**.

It increases with the increasing content of SiC particles, and MMCs made by the coated-reinforcement method show insignificantly higher levels of compressive strength compared to the composites made by the admixture method at the same level of compressive strain.

4 DISCUSSION

The density of the of the Al-SiC_p composites decreases with an increase in reinforcement volume fraction under the same processing conditions. This is because of the formation of porosity resulting from diffusive limitation of the matrix atoms bonded by the SiC_p. The porosity was mainly formed among the SiC particles as shown in **Figure 5**. In the case of noncoated reinforcement, clustering can occur more easily than in the case of coated reinforcement. This can lead to the formation of porosity after hot pressing. The densification of the composites can be improved by increasing the sintering pressure. In that case, the rupture of the SiC reinforcement takes place more easily at high volume fractions.

A higher reinforcement volume fraction and a higher porosity can hinder the electrical conductivity of the composites. The conductivity of a coated-reinforcement composite is higher than the conductivity of the admixture-method composite, due to the lower porosity and more efficient bonding of the Al-SiC_p interface.

The hardness and compressive yield strength are higher for composites made by the coated-reinforcement method. The poor mechanical properties of the admixture-method composite is due to the ineffective bonding between the contacting reinforcement units. The bonding strength between the Al matrix and the reinforcement unit will be reduced in this case and more brittle fracture can be initiated in these composites. That can make these composites weaker than those made by the coated-reinforcement method. The strength of the coated-reinforcement composites is better, the densification is higher, the interfacial bonding better, as is the ability to inhibit crack propagation.

5 CONCLUSIONS

The coated-reinforcement method was found to be a successful way to produce MMCs.

1. The quasi-uniform surface of an aluminum film can be formed on SiC particles by physical deposition. The film's depth increased with decreasing SiC particle size
2. Densification, strength, hardness and electrical conductivity increase in the case of coated reinforcement method.
3. The level of porosity appears to be higher in the admixture-method composites and it increases with an increasing volume fraction of reinforcement.
4. The coated-reinforcement method is effective for making composites with an increase in reinforcement content relative to the admixture method, because of the improved reinforcement-matrix bonding. The coating process does not increase the composite price much compared to the improvement in properties, because it does not depend on the amount of reinforcement, wheras some properties do. In the case of an electrically conducting reinforcement there is the possibility of using an electroplating process to coat the reinforcement, in some other cases electroless plating could be used. These are relatively cheap processes when compared to the contribution they make to the composite properties.

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