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Mechanical properties of aluminum matrix composite reinforced with titanium carbide

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Abstract. An original method for the production of metal matrix nanocomposites has been proposed, which consists of depositing carbide structures 4–12 nm thick onto the surface of particles of aluminum powder by molecular layering, mixing the resulting dispersed particles with particles of pure metal in the required concentration, then pressing and sintering the resulting mixture. The resulting workpieces are subjected to intense plastic deformation by high-pressure torsion, which not only significantly reduces porosity, ensures a uniform distribution of reinforcing particles throughout the volume, and destroys carbide shells on the surface of dispersed particles, but also grinds aluminum particles.

Experimental stress-strain curves of the synthesized composites were constructed and the contribution of various hardening mechanisms to the final hardening of the metal matrix composite was assessed.

In metal matrix composites synthesized by this method, with small fractions of the volume content of reinforcing titanium carbide particles (less than 0.1%), almost twofold hardening and a threefold increase in the yield strength are observed with a slight reduction in plastic deformation before failure.

1. Introduction

In recent decades, aluminum metal matrix composites have been widely used as structural materials due to their high performance properties. For reinforcement, both micro- and nanosized particles of silicon carbide (SiC), titanium carbide (TiC), boron carbide (B_4C), aluminum oxide (Al_2O_3) and various allotropes of carbon are most often used.

The transition to metal matrix reinforcement from microparticles to nanoparticles leads to a significant improvement in the mechanical properties of the metal matrix composite. This is primarily due to the fact that nanoparticles, compared to microparticles, have a greater ability to impede the movement of dislocations in the metal matrix and, therefore, more effectively increase the strength of composites. In addition, embedded nanoparticles can also lead to enhanced hardening effects of grain boundaries and matrix dislocations, inhibiting the initiation and propagation of cracks within nanoparticles or at particle/matrix interfaces, which helps improve the ductility of composites.

The strengthening of a metal matrix composite is influenced by a number of factors: the concentration of reinforcing particles, their geometry and size, differences in elastic

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moduli and thermal expansion coefficients, adhesion between the metal matrix and reinforcing particles, composite manufacturing technologies, and others. The factors listed above cause the appearance of barriers that prevent the movement of dislocations and determine the corresponding strengthening mechanisms, the interaction of which determines the observed strengthening. It should be noted that, along with a noticeable increase in strength and yield strength in metal matrix (nano)composites, there is a significant decrease in ductility, i.e. deformation until failure.

There are various liquid-phase and solid-state methods for preparing aluminum matrix nanocomposites containing different types of nanoparticles, such as stir casting, ultrasonic casting, selective laser melting, friction stir processing, accumulative pressing, powder metallurgy, etc. Although obtained through these processes nanocomposites may show increased strength compared to unreinforced aluminum matrix, their strength is still limited by the difficulty of introducing a uniform dispersion of high-content nanoparticles, because nanoparticles are more prone to aggregation in metal matrix than microparticles due to their volume-relative larger surface area, which becomes more significant when the volume fraction of reinforcing nanoparticles is high. In this context, achieving nanoscale uniform dispersion of reinforcing nanoparticles and preventing their coalescence are of key importance.

One of the ways to achieve a uniform dispersion of nanoparticles in metal matrix composites is the use of severe plastic deformation methods [1, 2], in particular, equal channel angular pressing (ECAP), accumulative rolling (ARB), and high-pressure torsion, which lead to both a decrease in porosity and uniform dispersion of reinforcing particles, as well as increasing strength properties [3–7].

The authors proposed an original method for the production of metal matrix nanocomposites, which consists of applying carbide structures 4–12 nm thick to the surface of aluminum powder particles by molecular layering, mixing the resulting dispersed particles with metal particles, then pressing and sintering the resulting mixture. After pressing and sintering, the resulting samples were subjected to intense plastic deformation by high-pressure torsion, which resulted in not only a decrease in porosity, a uniform distribution of reinforcing particles throughout the volume, and destruction of carbide shells on the surface of dispersed particles, but also grinding of aluminum particles. As a result, with the small volume fraction of reinforcing titanium carbide particles deposited on aluminum particles by the method of molecular layering, a large hardening is observed in the metal matrix composites synthesized by this method.

2. Description of a new technique for creating a metal matrix nanocomposites

The new technique we propose for creating metal matrix composites with nanosized reinforcing particles consists of the following steps.

At the first step, titanium carbide (TiC) nanolayers are synthesized on the surface of aluminum particles, the average size of which is from 50 μm to 100 μm, using the molecular layering method (“atomic layer deposition” (ML–ALD) [8, 9]). and provides a precise control of the thickness of the applied coating throughout the process, starting from the very first monolayer. Therefore, at any given time, it is possible to predict with a certain degree of accuracy the thickness of the applied coating for given conditions.

This method produced three types of dispersed aluminum particles with one, two and three layers of titanium carbide deposited on their surface. The thickness of each layer is 4 nm.

At the second step, these dispersed particles (Al&TiC) were compacted at a pressure of 200 MPa and sintered at a temperature of 600°C. The workpieces obtained after compaction have high porosity.

At the third step, in order to reduce porosity, additional compaction of the workpieces obtained at the previous stage was carried out using the high-pressure torsion method on a Walter Klement GmbH HPT-07 press. Ten revolutions were made at a speed of one revolution per minute with an applied pressure of 6 GPa. The diameter of the resulting blanks is 20 mm, and the thickness is 0.8 mm.

The volume content of titanium carbide in workpieces manufactured using this method depends on the number of layers deposited on the surface of aluminum particles, from 0.025% for one layer to 0.075% for three layers (table 1).

Table 1. Dependence of the volume fraction of TiC in workpieces on the number of layers deposited on the surface of Al particles.

Number of specimen	Matrix	Number of reinforcing layers	Mass fraction of TiC, wt.%	Volume fraction of TiC, %
1	Al	1 layer	0.04	0.024
2	Al	2 layers	0.08	0.048
3	Al	3 layers	0.12	0.072

As a result of high-pressure torsion, the coating layered on aluminum particles breaks down into individual reinforcing titanium carbide particles, the size of which is determined by the thickness of the titanium carbide layers. This method not only achieves a uniform distribution of reinforcing nanosized particles over the volume and reduces porosity [10, 11], but also grinds aluminum grains. In addition, reinforcing nanoparticles at the grain boundaries of the aluminum matrix prevent their fusion. It should also be noted that with an increase in the concentration of carbide particles, the size of aluminum grains decreases, which leads to hardening of the synthesized metal matrix composite.

3. Experiment and discussion

3.1. Experimental results

Tensile test samples are cut from blanks made by the above method. Figure 1 shows a manufacturing scheme that ensures uniformity of the properties of the working part of the sample and its dimensions.

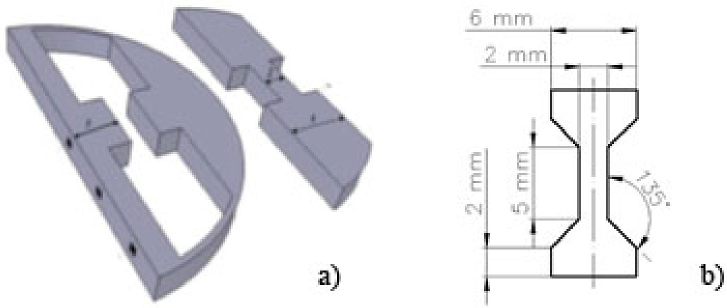

Figure 1. Sample: (*a*) cuttings from the workpiece, (*b*) dimensions.

Figure 2 shows experimental stress-strain curves for aluminum matrix nanocomposites synthesized from 100% dispersed powder of aluminum particles with one (4 nm), two (8 nm), and three layers (12 nm) of titanium carbide deposited on them.

Analysis of experimental results shows that, despite such a small volume fraction of reinforcing titanium carbide particles in the nanocomposite, all samples demonstrate a twofold increase in tensile strength and more than a threefold increase in yield strength compared to a sample of pure aluminum synthesized by the proposed method (see table 2).

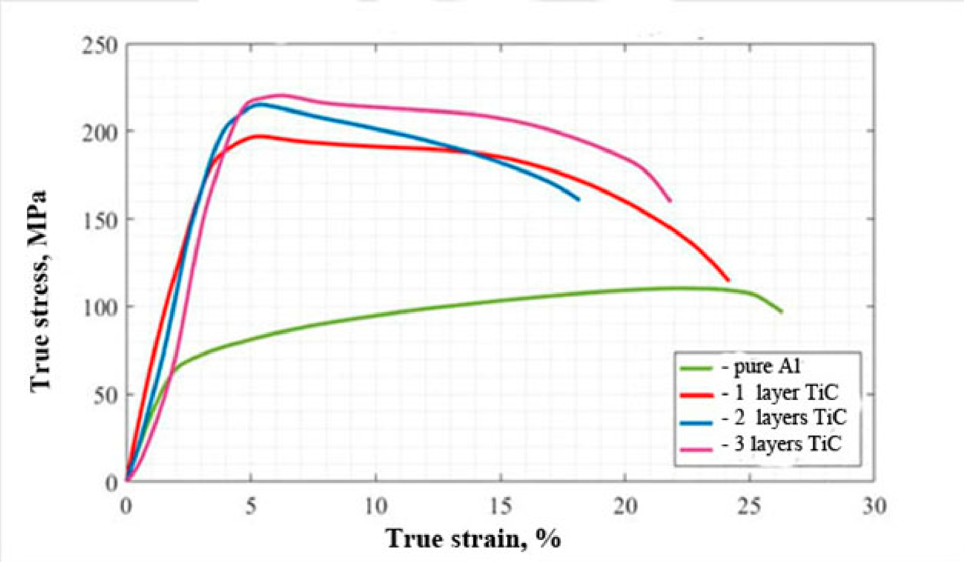

Figure 2. Stress-strain curves for aluminum matrix composites synthesized from 100% dispersed aluminum powder Al&TiC with one, two and three layers of titanium carbide.

Table 2. Dependence hardening of metal matrix nanocomposite Al&TiC on number of TiC layers.

	Number of TiC layers	Yield stress σ_T, MPa	Ultimate tensile strength, MPa
Al		50	110
Al&TiC	1	148	197
Al&TiC	2	162	215
Al&TiC	3	168	220

We draw attention to the fact that with standard reinforcement with carbide particles and such a significant hardening, the degree of plastic deformation is significantly reduced, which is not observed on the deformation curves obtained in our case. Apparently, this is due to the low concentration of reinforcing titanium carbide particles in the composite and the fact that after high-pressure torsion, the carbide coating on dispersed particles breaks up into particles whose diameter is about the thickness of the coating.

3.2. Discussion

Let us carry out a theoretical assessment of the contributions of hardening mechanisms to the final hardening of the composite under the assumption that the average diameters of titanium carbide particles after severe plastic deformation are equal to the thickness of the coating, i.e. 4 nm, 8 nm, and 12 nm.

Since the volume concentration of reinforcing particles is less than 0.1%, strengthening due to load redistribution, the mismatch between the thermal expansion coefficients of the matrix and the reinforcing material, and the appearance of an interphase layer between the reinforcing particles and the matrix can be neglected [12].

The experimentally observed strengthening of the synthesized nanocomposite is contributed by the strengthening caused by the dispersed phase (Orovan-Ashby), due to a mismatch between the elastic moduli of the matrix and inclusion materials, and due to matrix grain refinement (Hall-Petch).

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An estimate of the contribution of dispersion hardening can be obtained using the Orowan-Ashby formula [12]

$$\Delta\sigma_{\mathrm{Orow}} = \frac{0.13 G_{\mathrm{m}} b}{\lambda} \ln \frac{d_{\mathrm{p}}}{2b}, \quad \lambda = d_{\mathrm{p}} \left[\left(\frac{1}{2V_{\mathrm{p}}} \right)^{1/3} - 1 \right], \tag{1}$$

where $G_{\mathrm{m}} = 30\,\mathrm{GPa}$ is the shear modulus of the matrix, $b = 0.3 \times 10^{-9}\,\mathrm{m}$ is Burgers vector, V_{p} and d_{p} are the volume fraction and diameter of the TiC reinforcing particles, λ is the interparticle spacing.

Incremental hardening caused by geometrically necessary dislocations generated by the mismatch between the elastic moduli of the matrix and the reinforcing particle

$$\Delta\sigma_{\mathrm{EM}} = \alpha G_{\mathrm{m}} b \sqrt{\frac{8 V_{\mathrm{p}} \varepsilon}{b d_{\mathrm{p}}}}, \tag{2}$$

where α for aluminum is equal to 1.25, and ε is equivalent deformation [12].

When high-pressure torsion, the grains of the matrix are refined, accompanied by hardening of the material according to the Hall–Petch mechanism

$$\sigma_{\mathrm{Y}} = \sigma_0 + \Delta\sigma_{\mathrm{H-P}} = \sigma_0 + K \sqrt{\frac{1}{d_{\mathrm{Al}}}}, \tag{3}$$

where $\sigma_0 \approx 15\,\mathrm{MPa}$ and $K = 70\,\mathrm{MPa}\cdot\mu\mathrm{m}^{1/2}$ for aluminum, d_{Al} is the grain diameter, σ_{Y} is the yield strength [12].

Note that when fine-grained metals are deformed, knowing the yield strength of the metal after severe plastic deformation, it is possible to estimate the average grain size

$$d_{\mathrm{Al}} = \left(\frac{K}{\sigma_{\mathrm{Y}} - \sigma_0} \right)^2 = \left(\frac{K}{\Delta\sigma_{\mathrm{H-P}}} \right)^2 \tag{4}$$

To estimate the total contribution from individual hardening mechanisms, we will use the Klein additive model [13]

$$\Delta\sigma_{\mathrm{cy}} = \sigma_{\mathrm{Y}} - \sigma_0 = \Delta\sigma_{\mathrm{H-P}} + \Delta\sigma_{\mathrm{Orow}} + \Delta\sigma_{\mathrm{EM}}. \tag{5}$$

Using formulas (1), (2), (3), and (5), we estimate the contributions of individual hardening mechanisms to the total hardening.

Table 3 shows the experimentally observed ultimate tensile strength (column 3), yield strength σ_{Y} (column 4), and hardening $\Delta\sigma_{\mathrm{cy}}$ (column 5) for the obtained aluminum matrix composites with different volume fractions of reinforcing particles TiC.

The expected grain size of the aluminum matrix could be determined by the difference between the experimentally determined hardening $\Delta\sigma_{\mathrm{cy}}$ and the contributions of Orowan hardening $\Delta\sigma_{\mathrm{Orow}}$ and hardening due to the mismatch of elastic modules $\Delta\sigma_{\mathrm{EM}}$ found by formulas (1) and (2) using (4)

$$d_{\mathrm{Al}} = \left(\frac{K}{\Delta\sigma_{\mathrm{cy}} - \Delta\sigma_{\mathrm{Orow}} - \Delta\sigma_{\mathrm{EM}}} \right)^2 = \left(\frac{K}{\Delta\sigma_{\mathrm{H-P}}} \right)^2 \tag{6}$$

The average grain diameters of the aluminum matrix of the nanocomposite calculated by the formula (6) are given in column 9 of table 3.

Table 3. Dependence of Al&TiC nanocomposite hardening on number of TiC layers and average grain size.

	Number of TiC Layers	Ultimate tensile strength MPa	Yield stress σ_Y, MPa	$\Delta\sigma_{cy} = \sigma_Y - \sigma_0$, MPa	$\Delta\sigma_{Orow}$, MPa	$\Delta\sigma_{EM}$, MPa	$\Delta\sigma_{cy} - \Delta\sigma_{Orow} - \Delta\sigma_{EM}$, MPa	Size d_{Al}, nm
1	2	3	4	5	6	7	8	9
Al&TiC	1	197	148	133	46	19	68	1060
	2	215	162	147	40	19	88	633
	3	220	168	153	36	19	98	510
Al		110	50					4000

Conclusions

A new method has been proposed for introducing nanosized particles of titanium carbide into an aluminum matrix using dispersed aluminum particles with nanosized layers of titanium carbide deposited on their surface.

The use of the method of intense plastic deformation (high-pressure torsion) not only reduces the porosity of the composite and destroys the carbide coating applied to aluminum particles, but also significantly affects the structure of the matrix material, refining the matrix grain.

Despite the rather low volume concentration of titanium carbide in the composite (less than 0.1%), the strength more than doubles, and the yield strength increases threefold. .

The proposed method for the synthesis of a metal matrix composite using high-pressure torsion at the stage of reducing porosity significantly increases the strength properties of the metal composite without reducing ductility, even with small volume fraction of reinforcing material (TiC). It is a consequence of small sizes (less than 15 nm) and volume concentration (less than 0.1%) titanium carbide nanoparticles.

Acknowledgments

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