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Structure and properties of an aluminum-matrix composite reinforced with zirconium carbide particles

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Abstract. This study examines the structure and mechanical properties of aluminum-matrix composites (AMCs) with varying contents of the ZrC reinforcing phase, produced by powder metallurgy. Elemental mapping together with hardness measurements indicate a uniform distribution of ZrC particles in the matrix. The effects of mixing time (1–6 h), compaction pressure (636–1910 MPa), and sintering time (1–2 h) on density, porosity, and properties were investigated. With increasing ZrC content, the composite's mechanical properties improve, and correlations among density, porosity, hardness, and strength are observed. An increase in sintering time has little effect on density and porosity; after sintering, hardness decreases due to annealing. Local agglomeration of ZrC at grain boundaries may weaken interfacial bonding between aluminum and the reinforcement. Strengthening arises from load transfer, Orowan strengthening, and thermally induced dislocations due to the coefficient-of-thermal-expansion mismatch between the particles and the matrix. Efficient load transfer during compression testing requires good particle–matrix interfacial contact; dislocation–particle interactions generate Orowan loops, contributing to the observed strengthening.

Keywords: aluminum-matrix composites (AMCs), zirconium carbide, density, porosity, structure, morphology, hardness, strength, deformation

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Структура и свойства алюмоматричного материала, упрочненного частицами карбида циркония

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Аннотация. Представлены результаты исследования структуры и физико-механических свойств дисперсно-упрочненных композиционных материалов на основе алюминия с различным содержанием упрочняющей фазы ZrC, полученных методом порошковой металлургии. Согласно картам распределения химических элементов наполнителя и значениям твердости, частицы карбида циркония распределены в матрице равномерно. Изучено влияние времени перемешивания (от 1 до 2 ч) и усилия прессования (от 636 до 1910 МПа) на плотность, пористость и свойства образцов. С повышением количества частиц карбида циркония механические свойства композита улучшаются. Отмечена корреляция плотности, пористости, твердости и прочности композитов. Показано, что увеличение времени спекания практически не оказало влияния на плотность и пористость образцов. После спекания твердость образцов уменьшается вследствие отжига. Кроме того, скопления частиц ZrC на границах зерен могут ослабить химическую связь между алюминием и материалом наполнителя. В исследуемых композитах упрочнение происходит за счет следующих механизмов: передача активной нагрузки от матрицы к арматуре; усиления Орована; возникновение внутренних термических напряжений из-за разницы в коэффициентах теплового расширения между армирующими частицами и фазой матрицы. Эффективная передача нагрузки между пластичной матрицей и частицами жесткой керамической арматуры при испытаниях на сжатие происходит при наличии хорошего межфазного контакта между матрицей и арматурой. Взаимодействие между дислокациями и армирующими частицами увеличивает прочность композиционных материалов в соответствии с механизмом Орована. Благодаря наличию в матрице дисперсных частиц армирования, при взаимодействии дислокаций с армирующими частицами образуются дислокационные петли.

Ключевые слова: спеченный дисперсно-упроченный композиционный материал, карбид циркония, плотность, пористость, структура, морфология, твердость, прочность, деформация

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Introduction

Modern mechanical engineering, including the mining industry, is increasingly characterized by the use of new materials. The growing demand for lightweight materials with high specific strength, excellent high-temperature strength, and corrosion resistance stimulates active research and development of advanced high-performance materials [1–4].

Among light-weight materials with low density, aluminum-matrix composites (AMCs) occupy a leading position. The use of aluminum and its alloys as a matrix material continues to expand, finding broad applications in numerous industrial sectors due to their high strength and ductility, excellent thermal conductivity and corrosion resistance [5–7], as well as their relatively low cost compared to other light metals such as Mg and Ti [4; 8].

The global market for metal-matrix composites was estimated at USD 224.82 billion in 2023. It is projected to grow from USD 239.21 billion in 2024 to USD 369.29 billion by 2032, demonstrating a compound annual growth rate (CAGR) of 5.58 %. The increasing demand for lightweight materials in the mechanical engineering, automotive, and aerospace industries is expected to further stimulate key market drivers and contribute to market expansion[1].

The main limiting factor for the use of aluminum alloys is their relatively low hardness. Therefore, various reinforcements are incorporated into the matrix to enhance the physical and mechanical properties of aluminum-based materials. Metal-matrix composites (MMCs) are produced by different methods, including stir casting, die casting, spray forming, hot pressing, dynamic compaction, ultrasonic cavitation, physical vapor deposition, mechanical alloying, liquid-metal infiltration, and powder metallurgy (PM) [1; 2; 9; 10]. Most commercial MMCs are produced by liquid-phase methods with mechanical stirring, which makes it possible to obtain components of various sizes and geometries. However, these techniques have several drawbacks: low wettability of reinforcement particles by the molten matrix and the difficulty of achieving a uniform composite structure. Upon cooling and cessation of stirring, the reinforcement particles tend to distribute non-uniformly in the aluminum matrix, often forming agglomerates [1; 11; 12]. As a result, the composite may exhibit nonuniform mechanical behavior.

Unlike liquid-phase techniques, PM methods provide a uniform distribution of the dispersed phase within the aluminum matrix, usually prevent the formation of undesirable phases, and ensure strong interfacial bonding between the matrix metal and the reinforcing particles.

The PM method is energy-efficient, cost-effective, and technologically versatile for producing both simple and complex components of required dimensions. In recent years, PM processing has proven to be efficient and competitive compared with conventional casting methods in the fabrication of metal-matrix composites reinforced with ceramic particles. Composites fabricated by powder metallurgy generally exhibit lower density and higher porosity than those produced by stir casting; however, the reinforcement particles are uniformly distributed in the metallic matrix, unlike in stir-cast materials.

Aluminum-matrix composites produced by various methods are widely used in mechanical engineering [13], shipbuilding [14], electrical engineering [15], medicine [16] the aerospace [17] and defense [18; 19] industries, and even in consumer products [20].

Reinforcements typically include oxides, carbides, nitrides, fly ash, and carbon powders [1–3; 21; 22]. The choice of reinforcing particles depends on the intended application of the composite. The most commonly used dispersoids are SiC, TiC, ZrC, TiB_2,

[1] Metal matrix composites market size & share report. URL: https://www.marketresearchfuture.com/reports/metal-matrix-composites-mmcs-market-8131 (accessed: 16.05.2025).

B_4C, Al_2O_3, and Si_3N_4. Among them, zirconium carbide (ZrC) is one of the most suitable reinforcing materials for wear-resistant applications, seals, bearings, crucibles in the nuclear industry, and electronic devices. ZrC is characterized by a high melting point, specific strength, hardness, and corrosion resistance [23]. However, there are very few studies examining the effect of ZrC addition on the physical and mechanical properties of aluminum-matrix materials [24].

The aim of the present study is to investigate the structure and physical and mechanical properties of dispersion-strengthened aluminum-matrix composites reinforced with zirconium carbide (ZrC) particles.

Research methodology

The objects of study were aluminum-matrix composites containing different amounts of the ZrC reinforcing phase. Aluminum powder grade GOST 6058-73; 99 % purity; 250–450 μm) was used as the matrix. Zirconium carbide (ZrC) powder (GOST 28377-89; 40–100 μm) was served as the reinforcement.

The aluminum and zirconium carbide powders were mixed in a polystyrene cylinder rotating at 100 rpm for 1–6 h, with the rotation direction reversed every 15 min to enhance homogeneity.

The homogeneous powder blend was cold-pressed in a PGR-400 uniaxial hydraulic press using a hardened 40Kh steel die (ID 10.2 mm); industrial oil was applied to lubricate the die walls. The green compacts were sintered at 640 °C for 1–2 h under a protective carbon-powder layer and then furnace-cooled to room temperature.

SEM micrographs and EDS elemental maps of the aluminum-matrix composite were acquired on a Vega LMS (Tescan, Czech Republic) scanning electron microscope equipped with an Xplore30 EDS system (Oxford Instruments, UK). The microstructure was also examined using an Olympus BX61 research optical microscope (Olympus Corp., Japan).

The actual density was determined by measuring mass on an AND GR-300 electronic analytical balance (A&D Company Ltd., Japan), with volume obtained geometrically from micrometer measurements. Vickers hardness was measured on the sample surfaces using an ITV-30-AM tester (Metotest LLC, Neftekamsk, Russia) tester under a 25 N load and 15 s dwell; in accordance with GOST R ISO 6507-1-2007, five indents were made per sample. Compressive strength was measured on a MIM 2-20-2 universal testing machine (GOST LLC, Moscow, Russia) at a crosshead speed of 0.2 mm/s (GOST 25.503-97), with simultaneous stress–strain curve acquisition.

Results and discussion

Density and porosity are primary parameters for many applications. After cold compaction of the initial powder blend, the density of the material was measured in both the compacted and sintered states and compared with the theoretical density calculated by the rule of mixtures. The actual density was determined from the mass-to-volume ratio. Porosity was determined as the ratio of the difference between the theoretical and actual densities to the theoretical density. In estimating porosity, the theoretical density was assumed to remain unchanged during sintering because the composite constituents are mutually insoluble.

To select the optimal compaction pressure, trial runs were performed (Table 1). At $P = 636$ MPa, the compacts were friable, weak, and failed under slight load. Beginning at $P = 950$ MPa, dense compacts were obtained. Further increases in compaction pressure produced only minor changes in density (γ); therefore, all subsequent experiments used 980 MPa.

Analysis of the effect of compaction pressure shows that density increases with increasing reinforcement (carbide-phase) fraction (Table 1), owing to the higher density of the ZrC particles. After sintering, the density decreases. Theoretical densities exceed the measured values due to residual porosity, which likewise increases with increasing reinforcement content in the matrix.

With increasing reinforcement content, the porosity of the compacts initially rises linearly and then slows down, stabilizing at 7–10 wt. % reinforcement. After sintering, the porosity increases due to the expansion of air trapped during mixing of the initial powder blend. This expansion enlarges the pore volume and causes a corresponding change in the linear dimensions of the samples. Excessive addition of reinforcement particles also leads to matrix swelling of the sintered samples. Such porosity variations are consistent with the findings reported by other authors [1; 11].

According to the experimental data, both the “green” and sintered densities are governed by the combined and interacting effects of several factors, including compaction pressure, sintering conditions, and the compressibility of the reinforcing particles. As a result, the green and sintered densities deviate from the theoretical density of the composites.

Increasing the sintering time from 60 to 120 min had almost no effect on density and porosity, whereas for aluminum-matrix composites reinforced with SiC or Al_2O_3, an increase in sintering time from 60 to 90 min was reported to enhance density [11].

Table. 1. **Effect of compaction pressure on the density and porosity of the samples**

Таблица 1. **Влияние величины давления формования на плотность и пористость образцов**

Sample	*P*, MPa	γ_{theor}, kg/m^3	γ_{act}, kg/m^3		Porosity, %	
			before sintering	after sintering	before sintering	after sintering
Al	636	2700	1718	1652	36.37	38.81
	750		2081	2073	22.92	23.22
	900		2478	2469	8.22	8.56
	950		2572	2564	4.74	5.04
	960		2584	2576	4.29	4.59
	980		2604	2596	3.56	3.85
	1273		2610	2602	3.33	3.63
	1910		2612	2601	3.26	3.67
Al–4%ZrC	636	2861	1840	1832	35.68	35.96
	900		2630	2622	8.07	8.35
	950		2747	2738	3.98	4.29
	980		2760	2752	3.53	3.81
	1273		2765	2757	3.35	3.63
	1910		2769	2761	3.22	3.49
Al–7%ZrC	636	2982	1914	1906	35.81	36.08
	980		2871	2865	4.62	4.81
	1273		2875	2864	3.59	3.96
	1910		2882	2872	3.35	3.69
Al–10%ZrC	636	3103	1947	1941	37.25	37.44
	980		2984	2978	3.86	4.03
	1273		2998	2987	3.38	3.74
	1910		3007	2998	3.09	3.38

The surface morphology and elemental distribution of the synthesized samples are shown in Figs. 1 and 2. In all cases, a smooth and relatively even surface was observed. The measured surface roughness of the sample cross section was R_a = 1.0–1.2, corresponding to fine turning. Elemental mapping confirmed a sufficiently uniform distribution of the constituent elements.

The high detected oxygen content, and correspondingly lower total aluminum content, are explained by the formation of an Al_2O_3 film on the aluminum surface exposed to air (2 mol Al → 3 mol O). According to the analysis, the ratio was 1.87 mol Al and 2.64 mol O. This oxygen amount oxidizes most of the surface aluminum (1.76 mol Al), leaving 0.11 mol Al unoxidized.

Hardness is one of the key parameters directly influencing the strength, impact toughness, fatigue strength, and wear resistance of metal-matrix composites. It is well known that hardness testing is one of the most informative and rapid methods for assessing mechanical properties.

For the composites investigated in this study, variation of the mixing time from 1 to 6 h had virtually no effect on hardness (Fig. 3).

Increasing the sintering time from 60 to 120 min caused a 3.7–8.6 % increase in hardness (Fig. 4). However, as the reinforcement content increased, the relative hardness change decreased, approaching a steady value of 3.7–3.8 %.

To assess the uniformity of particle distribution, hardness measurements were taken along the polished surface of the sintered samples at 2.5 mm intervals. The small variation in hardness (±2.6 %) confirmed uniform particle dispersion in the aluminum matrix, consistent with the elemental maps.

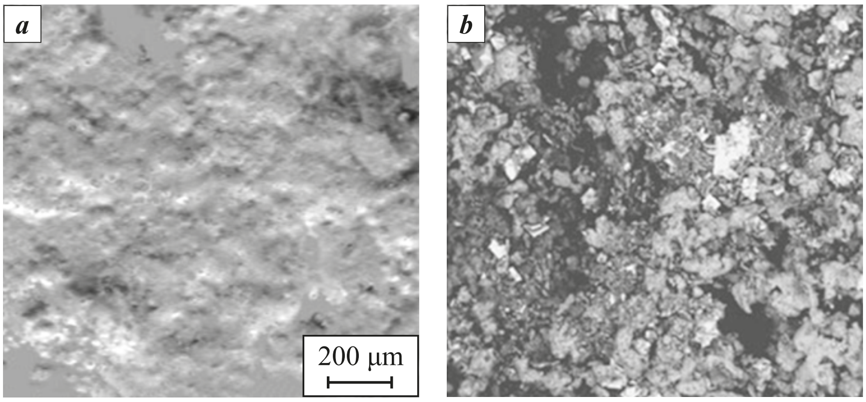

Fig. 1. SEM images of the surface of an Al–5%ZrC sample
a – SEM secondary-electron (SE) image; ***b*** – SEM backscattered-electron (BSE) image

Рис. 1. Морфология поверхности образца Al–5%ZrC
a – топо изображение; ***b*** – электронное изображение

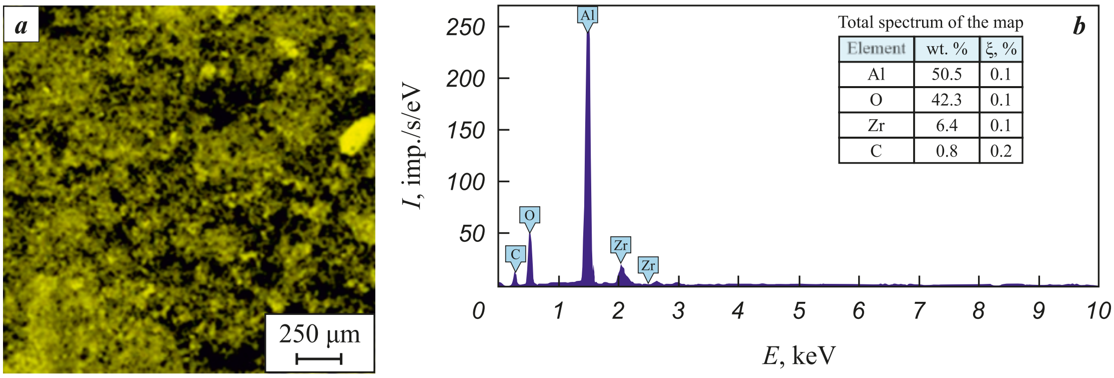

Fig. 2. Elemental distribution map and corresponding EDS spectrum
a – surface of the Al–4%ZrC sample; ***b*** – EDS spectrum showing elemental composition

Рис. 2. Карта распределения элементов
a – по поверхности образца Al–4%ZrC; ***b*** – суммарное распределение элементов

With increasing ZrC content in the aluminum matrix, the composite hardness increased (Table 2). After sintering, hardness decreased due to annealing. In addition, clustering of ZrC particles at grain boundaries may weaken interfacial bonding between aluminum and the reinforcement.

Previous studies have reported a correlation between hardness and density (or porosity) of the samples [1; 3; 6; 7]. A similar proportional relationship between hardness and density (porosity) was also observed in this study (Fig. 5).

The compressive strength of the composites was determined by compression testing. Unlike tension tests, not all materials can be brought to failure under compression, as ductile metals such as aluminum tend to deform into thin plates.

With increasing reinforcement content, the compressive strength increased similarly to hardness. Composites containing carbide particles exhibited a substantial strength improvement compared with the unreinforced aluminum matrix, indicating that ZrC particles provide a strong strengthening effect.

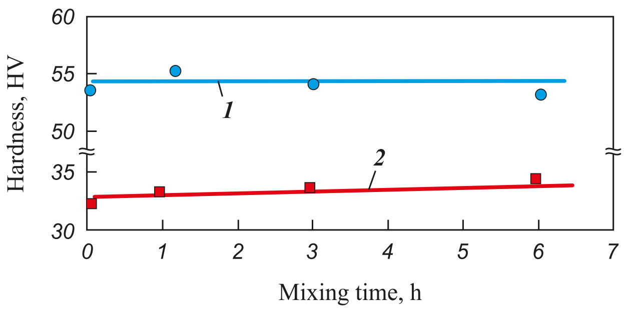

Fig. 3. Effect of mixing time on the hardness of Al–4%ZrC samples
1 – before sintering; ***2*** – after sintering

Рис. 3. Влияние времени перемешивания на твердость образцов Al–4%ZrC
1 – до спекания; ***2*** – после спекания

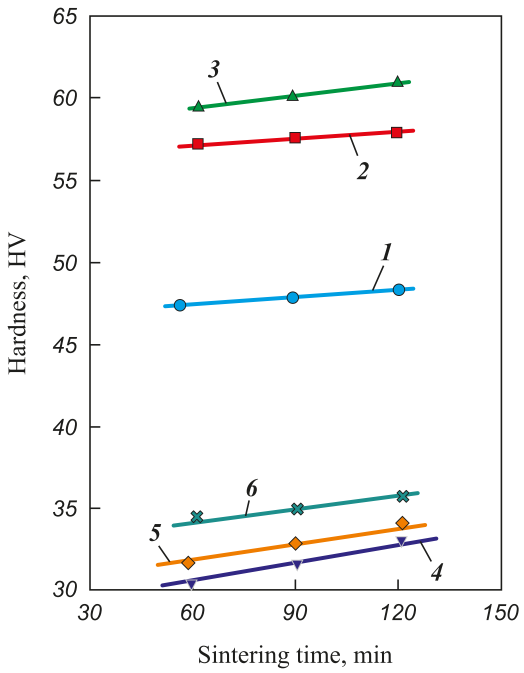

Fig. 4. Effect of sintering time on the hardness of the samples

1–3 – before sintering; ***4–6*** – after sintring
1, ***4*** – Al–0%ZrC; ***2***, ***5*** – Al–4%ZrC; ***3***, ***6*** – Al–10%ZrC

Рис. 4. Влияние времени спекания на твердость образцов

1–3 – до спекания; ***4–6*** – после спекания
1, ***4*** – Al–0%ZrC; ***2***, ***5*** – Al–4%ZrC; ***3***, ***6*** – Al–10%ZrC

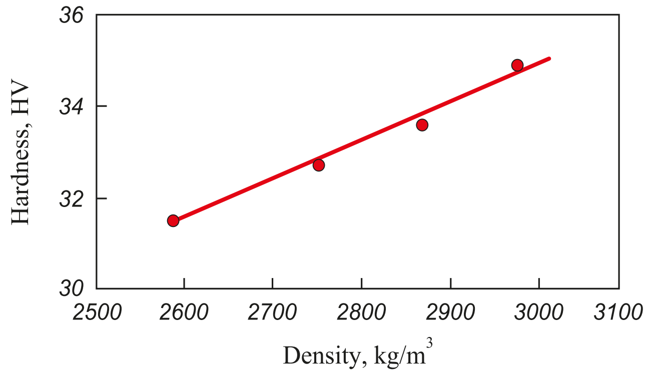

Fig. 5. Effect of density on the hardness of Al–ZrC samples after sintering

Рис. 5. Зависимость твердости от плотности образцов Al–ZrC после спекания

As the ZrC content increased, both the ultimate strength and yield strength of the composites rose (Fig. 6). The strengthening can be attributed to the higher dislocation density and the role of carbide particles as barriers to dislocation motion.

The relative strength increase of the composites compared with the aluminum matrix ranged from 20 to 50 %. The addition of carbide particles to an aluminum alloy has a positive effect on mechanical properties. The obtained results are consistent with the reported compressive strength of Al–ZrC composites produced by powder metallurgy [24] and by friction stir processing method [25].

Several strengthening mechanisms contribute to the improved performance of metal-matrix composites, the most important being thermal-expansion mismatch and elastic-modulus mismatch between the matrix and the reinforcement (Hall–Petch relationship and Orowan mechanism).

In the studied composites, strengthening arises from load transfer from the matrix to the reinforcement, Orowan strengthening, and the generation of internal thermal stresses due to the difference in the coefficients of thermal expansion (CTE) between the reinforcement particles and the aluminum matrix. Effective load

Table 2. Effect of composition on the hardness of composites

Таблица 2. Влияние состава на твердость композитов

Sample	Hardness, HV	
	before sintering	after sintering
Al–0%ZrC	48.38	31.44
Al–4%ZrC	57.42	32.76
Al–7%ZrC	59.75	33.57
Al–10%ZrC	60.42	34.88

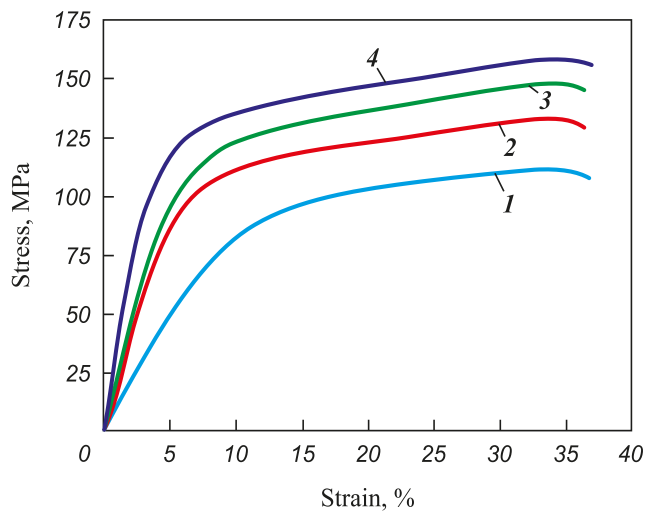

Fig. 6. Compression stress–strain curves of the samples

1 – Al–0%ZrC; ***2*** – Al–4%ZrC; ***3*** – Al–7%ZrC; ***4*** – Al–10%ZrC

Рис. 6. Диаграммы деформации образцов, полученные при испытаниях на сжатие

1 – Al–0%ZrC; ***2*** – Al–4%ZrC; ***3*** – Al–7%ZrC; ***4*** – Al–10%ZrC transfer between the ductile matrix and hard ceramic reinforcement particles during tension or compression occurs when good interfacial contact exists between the two phases.

Interactions between dislocations and reinforcement particles enhance the composite strength according to the Orowan mechanism. The presence of dispersed reinforcement particles in the matrix leads to the formation of dislocation loops as dislocations bypass the particles.

Conclusion

Based on the results of the conducted study, the following conclusions can be drawn:

1. Fabrication of Al–ZrC composites by the powder metallurgy method ensures a uniform distribution of zirconium carbide particles within the aluminum matrix, as confirmed by microstructural observations and hardness measurements.

2. Increasing the zirconium carbide content from 0 to 10 wt. % leads to higher density and porosity of the aluminum-matrix composite. The porosity of the samples initially increases linearly with reinforcement content, followed by a slowdown and stabilization at 7–10 wt. % reinforcement.

3. The hardness and strength of the composites increase proportionally with reinforcement content. With a zirconium carbide content of up to 10 wt. %, the hardness and strength of the composites rise by 11 and 52 %, respectively.

4. Increasing the mixing time from 1 to 6 h has little effect on the hardness of the composite material: the relative change was 0.5–0.8 % for green compacts and 2.6–3.2 % for sintered samples.

5. With an increase in sintering time from 1 to 2 h, hardness of the samples rises from 3.7 to 8.6 %, but as the reinforcement content in the matrix increases, it decreases and approaches a steady value of 3.7–3.8 %.

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