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Experimental analysis of wear resistance of compacts of fine-dispersed iron powder and tungsten monocarbide nanopowder produced by impulse pressing

Anatoly M. Bragov [a], Leonid A. Igumnov [a], Alexander Yu. Konstantinov [a], Andrey K. Lomunov [a], Evgeny E. Rusin [b], Victor A. Eremeyev [a,c,*]

[a] Research Institute for Mechanics, Nizhniy Novgorod Lobachevski State University, Nizhny Novgorod, 603950, Russia
[b] Institute of Mechanical Engineering Problems, RAS, Nizhny Novgorod, 603950, Russia
[c] Faculty of Civil and Environmental Engineering, Gdańsk University of Technology, 80-233 Gdańsk, Poland

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ABSTRACT

The paper presents the results of studying the structure and wear resistance of compacts produced from fine dispersed reduced iron powder (average particle size 3–5 μm) with the addition of tungsten carbide (WC) nanopowder with the average particle size of 25–30 nm. The mass fraction of tungsten carbide (wolfram carbide) in the powder composition was 5% and 10% of the total mass. Impulse pressing was conducted using the modified Kolsky method at compacting temperatures of 20 °C to 300 °C. The produced compacts had relative density of over 90%.

Metallographic studies using the scanning electronic microscopy method on a TESCAN VEGA II electronic microscope have shown that the produced compacts have a fairly homogeneous fine-grained structure, with a uniform pattern of pore distribution, the form of the pores being close to spherical. X-ray microanalysis using an INCA Energy 250 energy-dispersion spectrometer with scanning along the surface line and transversal laps testifies to the fact that, in the considered temperature range, dynamic compaction does not lead to any noticeable changes in the distribution of the Fe, W and C elements over the bulk of the specimens. The conducted measurements of micro-hardness of the compacts have shown that it increases considerably with the pressing temperature.

The produced compacts were tested for wear resistance in a dry friction regime, using the 'rotating disk – stationary specimen' configuration. Mass loss of the compacts as a function of testing time is presented. Wear resistance of compacts depends on pressing temperature and concentration of the WC powder in the matrix of reduced iron. It has been experimentally determined that maximal wear resistance is observed in the compacts with the mass fraction of WC equal to 10%, produced at a pressing temperature of 300 °C.

1. Introduction

In many fields of mechanical engineering, compacted materials, produced by dynamic pressing methods from nanopowders and compositions thereof, are widely used in producing parts of various micromechanisms [1,2]. The most important characteristic of such materials is their high wear resistance, which determines their applications in the engineering. In addition, it is possible to use the material in miniature transmission devices, clutch devices and brake systems operating in dry friction conditions. Micro nodes with high wear resistance can be made from the obtained compacts using laser dimensional processing, which excludes structural changes in the material in the cutting zone [3].

The key stage in the producing technology of compacted materials is forming high-quality pressings (compacts) of required geometries from powders of various granulometric compositions — large-grained powders, nanopowders and combinations thereof. Many powder compositions, including nanopowders, have unique physical-mechanical properties and functional characteristics. The presence of nanometer and submicron structural elements in large-grained powders may result in increased crack resistance, impact elasticity, wear resistance, strength and hardness of the material. In the process of compaction, uniform distribution of density in the compacts is to be provided to obtain high-quality products having required properties. It is important

* Corresponding author at: Faculty of Civil and Environmental Engineering, Gdańsk University of Technology, 80-233 Gdańsk, Poland.
E-mail addresses: bragov@mech.unn.ru (A.M. Bragov), Igumnov@mech.unn.ru (L.A. Igumnov), constantinov.al@yandex.ru (A.Yu. Konstantinov), lomunov@mech.unn.ru (A.K. Lomunov), eerusin@mail.ru (E.E. Rusin), eremeyev.victor@gmail.com (V.A. Eremeyev).

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to provide chemical purity and a desired phase composition of the manufactured products [1,4].

There are several directions in the production of powder compositions consisting of nano- and ultrafine particles: static and dynamic pressing, vibration, isostatic pressing, extrusion, sintering under pressure, spark plasma sintering, shock wave pressing, severe plastic deformation. It was noted in [5,6] that the conventional powder-metallurgical process of fabricating composites consists of mixing matrix and reinforcing powders, cold isostatic pressing (CIP), vacuum sintering and hot isostatic pressing (HIP) or hot working. However, the process is difficult for production of composites having relatively high contents of reinforcements because of difficulties in uniform mixing, cold compaction and also the size control of the reinforcements.

Therefore, dynamic compaction methods are used for these purposes: explosive, magneto-pulsed [7], which are distinguished by the complexity and variety of physical processes that affect the deformation of individual powder particles and the consolidation of the porous preform as a whole. Contributions of particular mechanisms into the compaction process can differ, depending on the material of the pressed powder, size and form of its particles, pressure pulse amplitude and duration as well as on pressing temperature. Strength of compacted materials in any pressing method is directly related to the consolidation degree in inter-particle contact zones. In powder metallurgy, the consolidation degree is, as a rule, connected with the area of juvenile (renewed) surfaces of the powder particles, formed due to their deformation in the pressing process [5].

As it is well-known [6,8], pulsed loading of porous and powder systems is accompanied by intensive plastic deformation and local heating of material particles. In the case of metal powders, juvenile surfaces of pure metal are formed as a result of fracture of the surface layers of the particles in the process of their deformation. High temperatures promote activation of juvenile surfaces and formation of metallic bonding in the contact zone. The consolidation degree of the powder particles is determined by a number of mechanical properties of the material, such as, for instance, elastic moduli, as well as by compaction temperature.

An analysis of the results of numerous experimental and theoretical studies suggests that the basis of any wear models is the relationship between the external (force, energy, chemical, etc.) impact of a certain intensity and the utmost characteristics of certain volumes of materials that oppose this effect. It is believed that the forces of frictional interaction in the contact zone substantially depend not only on the nature of the materials of the contacting surfaces, but also on the spatial parameters of their relief and other characteristics. The variety of processes occurring on the friction surfaces served as the basis for the development of wear models.

The relationship between surface roughness and friction and wear characteristics is discussed in [9–11]. It was shown in [9] that interdependent irregularities have a fundamental effect on friction in contact with solids through the theoretically obtained shear-force–displacement relation. The ratios obtained in this work can be used to evaluate adhesion, ductility, and surface damage. Misra in [10] used the micromechanical methodology, which takes into account the interactions of rudeness and surface roughness, characterized by a statistical distribution of the amplitudes of the roughness and the orientation of the contact of the roughness. The results obtained using the proposed model are of great importance for modeling the evolution of surface crack behavior in friction experiments.

The aim of the present paper is an experimental analysis of the effect of pressing temperature and composition of the combination of fine-dispersed reduced iron and tungsten (wolfram) monocarbide nanopowder on wear resistance of compacts produced by impulse pressing.

2. Materials and investigation methods

Tungsten carbide (WC) is widely used in the production of hard alloys, which are the main part of all tool materials [12,13]. In particular, WC was used to improve wear properties of coatings [14,15]. Recently, active investigations have been conducted in the field of using tungsten carbide in its nano-crystalline state, which, potentially, can improve exploitation properties of materials containing WC. WC powder is a hardly-deformable powder even in the conditions of dynamic pressing, necessitating use of highly-plastic reduced iron powder as a matrix. The present work studies the possibility of adding WC nanopowder as a component to increase strength, hardness and wear resistance of the main powder material, the compact thereof can be then used for producing parts working in the conditions of dry friction in various micro-mechanisms and devices.

Here we study such powder materials as the reduced iron powder (with the average particle size of 8–10 μm) with the addition of WC nanopowder (average particle size of 25–30 nm) (Fig. 1). The mass fraction of tungsten carbide was 5% and 10% of the total mass.

Theoretical density of the powder mixture was determined according to the mixture rule:

$$\rho_{\text{mix}} = \rho_{\text{WC}} X + \rho_{\text{Fe}}(1 - X), \tag{1}$$

where $\rho_{\text{WC}} = 15.77$ g/cm^3 is the density of WC; $\rho_{\text{Fe}} = 7.874$ g/cm^3 is the density of iron; X is the percentage of WC in the mixture. So the resulting theoretical densities of the powder mixtures were the following: for the mixture Fe+5%WC – 8.270 g/cm^3, and for Fe+10%WC – 8.667 g/cm^3, respectively.

The powders were mixed as follows. About 80 g of chemically pure acetone was added to a mixture of powders (~40–50 g); the suspension was treated in an ultrasonic bath during 20 min. Then the acetone was evaporated using a fan in a drying box at a temperature of 60 °C. Prior to impulse compacting, the powder material underwent preliminary static compression.

Dynamic compaction of the powder materials in the present work was done using a modification of the Kolsky method [8,16–19] making it possible to control loading parameters and to choose rational regimes of compaction of the powder materials with the loading pulse duration in the range of 100–400 μs and pressure amplitudes of up to 2000 MPa.

Experiments were conducted on a stand (Fig. 2), comprising a loading unit, two measuring bars, each 20 mm in diameter, and a set of registering and synchronizing instruments [16–18]. A 20 mm-caliber gas gun was used as a loading unit. The powder under study was placed in a special high-strength cartridge with the inner diameter of 7 mm, located between the ends of the measuring bars. Strain was measured using strain gauges cemented onto the side surface of the bars. Signals from the strain gauges were registered with a digital oscillograph. To transfer force from a loading bar with a diameter of 20 mm to a compact specimen with a diameter of 7 mm, punches made of high-strength steel were used.

An accelerated impactor strikes a loading bar and excites in it a one-dimensional elastic compression wave $\varepsilon^I(t)$, which propagates in the bar at a speed C. When the wave reaches the specimen it splits into two ones because of different acoustic impedances of the bar and the specimen materials as well as their different cross-sections. The first wave $\varepsilon^R(t)$ is reflected back into the loading bar while the second wave $\varepsilon^T(t)$ passes through the specimen into the transmitting bar. The specimen experiences elastoplastic deformation while the bars undergo elastic deformation. Amplitudes and shapes of the waves $\varepsilon^R(t)$ and $\varepsilon^T(t)$ are dependent on the ratio between acoustic impedances of the bar and the specimen and on response of the specimen material to dynamic load applied. These strain pulses were measured using strain gauges cemented onto the side surface of the bars. Signals from the strain gauges were registered with a digital oscilloscope.

Based on the data about the registered elastic strain pulses in the both bars it was possible to determine time histories of stress $\sigma_s(t)$,

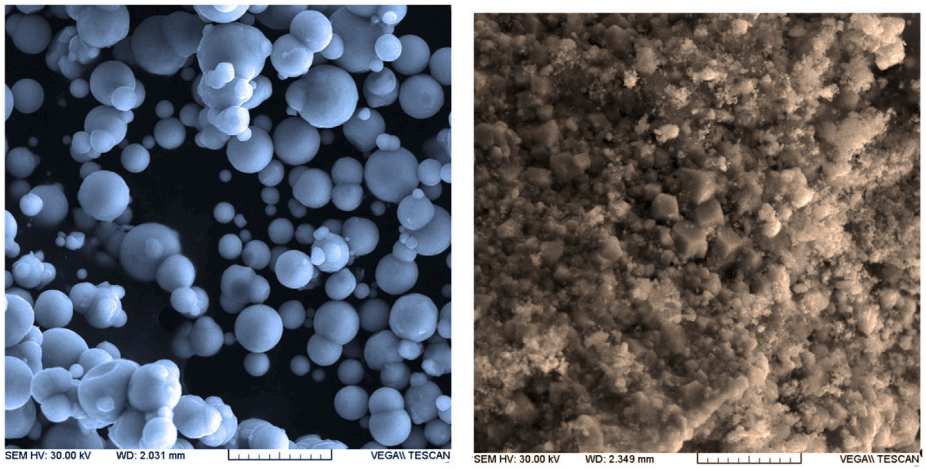

Fig. 1. Particles of iron powder (a) and of tungsten monocarbide (b).

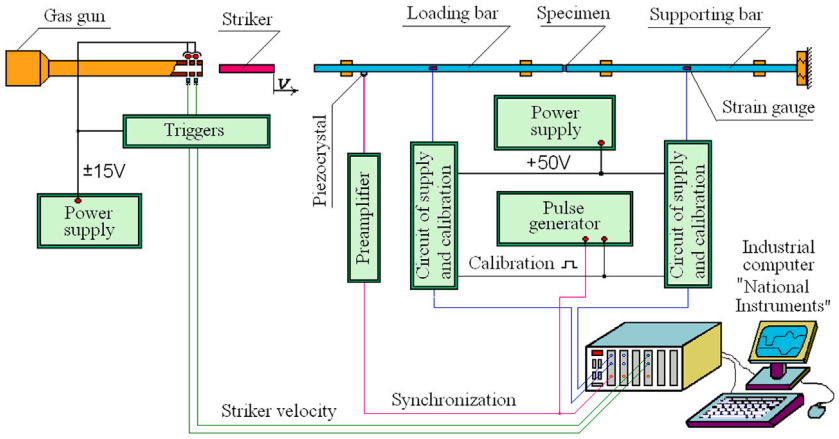

Fig. 2. The scheme of the experimental stand for impulse pressing of powder materials.

strain $\varepsilon_s(t)$ and strain rate $\dot{\varepsilon}_s(t)$ in the powder material specimen during the process of compaction as follows [19, Sect. 1.3]

$$\sigma_s(t) = \frac{EA}{A_s}\varepsilon^T(t), \quad \varepsilon_s(t) = -\frac{2C}{L_s}\int_0^t \varepsilon^R(t)\,dt, \quad \dot{\varepsilon}_s(t) = -\frac{2C}{L_s}\varepsilon^R(t), \tag{2}$$

where $\varepsilon^I(t)$, $\varepsilon^R(t)$ and $\varepsilon^T(t)$ are incident, reflected and passed strain pulses in the measuring bars, respectively. In other words, $\varepsilon^I(t)$ is an incident strain pulse in the loading (incident) bar, $\varepsilon^T(t)$ is a strain pulse in the supporting (transmission) bar, and $\varepsilon^R(t)$ is a reflected pulse in the loading bar, see [19, Sect. 1.3] for more details. In addition, C is velocity of elastic waves in the bars, E and A are Young's modulus and cross-section area of the measuring bars, respectively, L_s is initial length of the specimen, A_s is the cross-section area of the specimen, and the subscript "s" denotes specimen-related quantities.

Based on the change of the specimen height given by

$$h_s(t) = C\int_0^t \left[\varepsilon^I(t) - \varepsilon^R(t) - \varepsilon^T(t)\right]\,dt, \tag{3}$$

we can obtain a diagram of the change of density of the compact during the pressing as follows

$$\rho(t) = \rho_0 + \frac{4mh_s(t)}{\pi d^2 L_s^2}. \tag{4}$$

Here m and ρ_0 are initial mass and mass density of the specimen, respectively, and d is its diameter.

The above-described experimental stand makes it possible to vary strain rates in a wide range. To cover the entire range, strikers are first fired with different initial velocities; in order to provide sufficient strain values at lower velocities, longer strikers are used. 400 mm long strikers of steel 30HGSA were used in the experiments.

To assess the structure of the resulting compacts, their metallographic analysis was done using the scanning electronic microscopy on a TESCAN VEGA II electronic microscope with the magnification of x100 to x20000. Besides, X-ray microanalysis was done, using an INCA Energy 250 energy-dispersing spectrometer in the regime of scanning along the surface line and transversal laps of the produced compacts, which made it possible to observe changes of the relative concentration of particular elements (Fe, W, C) along the chosen line on the electronic picture.

Micro-hardness of the compacts was measured using a standard micro-durometer.

Tribological wear tests of the obtained compacts were carried out at ambient temperature according to the loading scheme 'counterbody (rotating disk) — stationary specimen' in the dry friction mode (Fig. 3).

The counterbody (a rotating disk 4 mm thick and 40 mm in diameter) was made of HSS-M2 tool high-speed steel (Table 1), hardened to a hardness of 63 HRC. The roughness of the lateral surface of the disk was $R_a = 1.6$ μm.

The microstructure of HSS-M2 steel after standard heat treatment, including quenching from 1230 °C in oil and subsequent triple tempering at 560 °C, consists of tempered martensite and solid carbides of the type M_6C and MC of a spherical shape with a diameter of less than 3 μm. The carbide particles are uniformly distributed in the

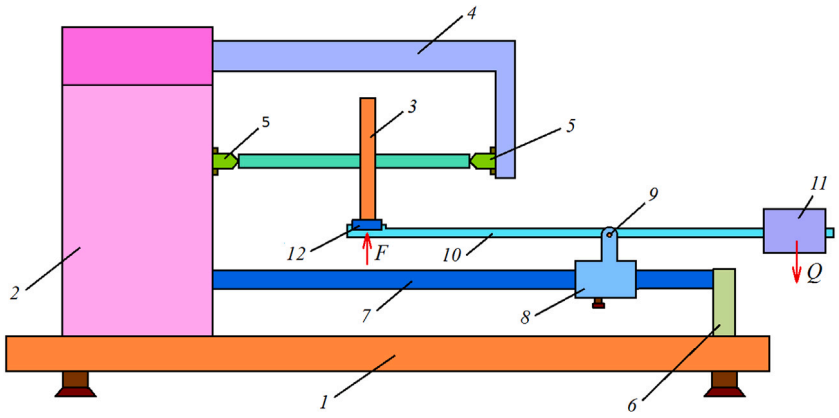

Fig. 3. Functional schema of the stand for the study of wear; 1 — base, 2 — drive, 3 — counterbody, 4 — console, 5 — rotating center, 6 — support, 7 — guide rails, 8 — carriage, 9 — bearings, 10 — lever, 11 — load, 12 — specimen.

Table 1
The chemical composition of high-speed steel HSS-M2 (AISI/ASTM).

C	Si,	Mn	Ni	S	P	Cr	Mo	W	V	Co
0.82–0.9	≤ 0.5	≤ 0.5	≤ 0.4	≤ 0.025	≤ 0.03	3.8–4.4	4.8–5.3	5.5–6.5	1.7–2.1	≤ 0.5

matrix and are close to the regular spherical shape. The method of X-ray diffraction analysis showed that the carbides in this steel are M_6C and MC, which have a complex FCC crystal lattice and the Fd_3m space group. M_6C spherical carbides correspond to the composition of Fe_3W_3C, and MC spherical carbides correspond to the composition of VC. Such a microstructure provides the highest hardness values for this steel.

3. Results

Impulse pressing of all the powder mixtures was done in the same loading conditions (pressure pulse duration of 300–350 μs with the amplitude ~1500 MPa). To study the effect of temperature on the mechanical properties of the compacts, impulse pressing was conducted at temperatures of 20, 100, 200 and 300 °C. A cartridge with the powder was heated by a special heating device with heat control. Prior to impulse compacting, the powder mixture was heated up to 100 °C in 10–15 min, then up to 200 °C in 15–25 min and finally up to 300 °C in 25–35 min. In each experiment, the loading parameters (loading wave amplitude and duration, determined by the velocity and length of the striker, preheating temperature) were registered, as well as strain pulses in the measuring bars, which were used to construct dynamic pressing diagrams of the powders.

As a result of the experiments, cylindrical compacts with a diameter of 7 mm and lengths from 2.6 mm up to 3.5 mm were produced. The roughness of the end surfaces of the obtained compacts was determined by the roughness of the end surfaces of the punches and was no worse than $Ra = 0.1$ μm.

The conducted studies have shown that density of the produced compacts increased with the pressing temperature. Density was determined by measuring the mass and volume of the compact. The volume was found using the hydrostatic weighing method. Relative density of the compacts was found as a ratio of the determined density of the compact and the theoretical density of the initial powder mixture, given earlier by (1).

Table 1 summarizes the main characteristics of the compacts produced from the mixtures of Fe+5%WC and Fe+10%WC at preheating temperatures of 20, 100, 200 and 300 °C. The last column of Table 1 shows the increase of microhardness of the compacts obtained at elevated preheating temperatures relative to the microhardness obtained at room temperature.

To understand the mechanism of compaction of the Fe+5%WC and Fe+10%WC powders in the process of pressing at different temperatures, compaction diagrams (time histories of the axial stress and density in the process of compression) were constructed (Figs. 4 and 5). As is evident from the diagrams, apart from preheating, the initial density of the powder mixtures makes a considerable contribution into the compaction process. It can be seen that compaction of the powder takes place not only when the maximum of the pressure pulse is attained, but also during relaxation of pressure.

It is known [4] that compaction of powder under applied loading is realized both due to relative motion of the powder mixture particles and due to plastic deformation of the powder particles. At the initial stage of the pressing process, the largest contribution into compaction is made by relative motion and by filling the gaps between bigger particles with smaller ones. At the final stage of the pressing process, compaction is realized mainly due to plastic deformation of particles.

The conducted microstructural analysis has shown that the produced compacts have a fairly homogeneous fine-grained structure; the general pore distribution pattern is uniform, the pore geometry being a distorted spherical shape or the shape of deformed semi-regular polyhedral. Local zones of elevated temperatures have been found along the particle boundaries in the pore filling locations.

Based on the results of X-ray microanalysis of the produced compacts, we have been found that dynamic compaction in the considered temperature range does not lead to any noticeable redistribution of the elements of Fe, W and C over the bulk of the specimens.

A metallographic analysis of the obtained compacts showed that in the structure of the compacts there are zones with local elevated temperatures, located along the boundaries of the particles, at the points of pores filling out.

Fig. 6 shows photographs of the surface of compacts with an increase of x10000 obtained at various pressing temperatures.

An analysis of the structures of the obtained compacts showed that preheating of the powder material leads to a more uniform release of energy over the surface of the particles. In the process of pressing the powder mixture, the particles are first repackaged: the particles move together and the small particles fill the gaps between the large ones. The particles are then compacted by plastic deformation until the plasticity of the powder particles is exhausted. Regardless of further increase of applied load, threshold density of powder body is achieved, further increase of which is impossible without change of

Table 2
The main characteristics of the compacts.

Preheating temperature, °C	Density, kg/m^3	Relative density, %	Final deformation, %	Mean value of micro-hardness, MPa	Increase of micro-hardness
Fe + 5%WC					
20	7147.83	86.43	26.60	1125	1.00
100	7366.31	89.07	28.82	1846	1.64
200	7702.54	93.14	31.20	2385	2.12
300	7895.28	95.47	33.50	2669	2.37
Fe + 10%WC					
20	7349.90	84.80	27.23	1902	1.00
100	7349.90	84.80	27.23	1902	1.00
200	7819.78	90.22	31.39	2641	1.39
300	8084.06	93.27	32.55	2885	1.52

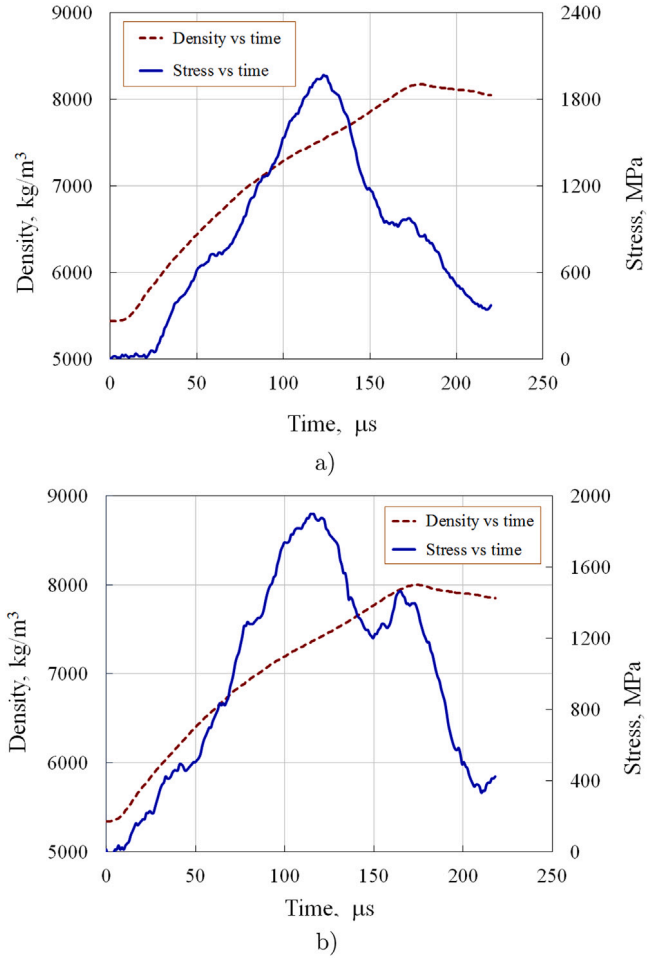

Fig. 4. Time history of the compaction process (density, stress) for the Fe+5%WC powder mixture at a temperature of 20 °C (a) and 300 °C (b).

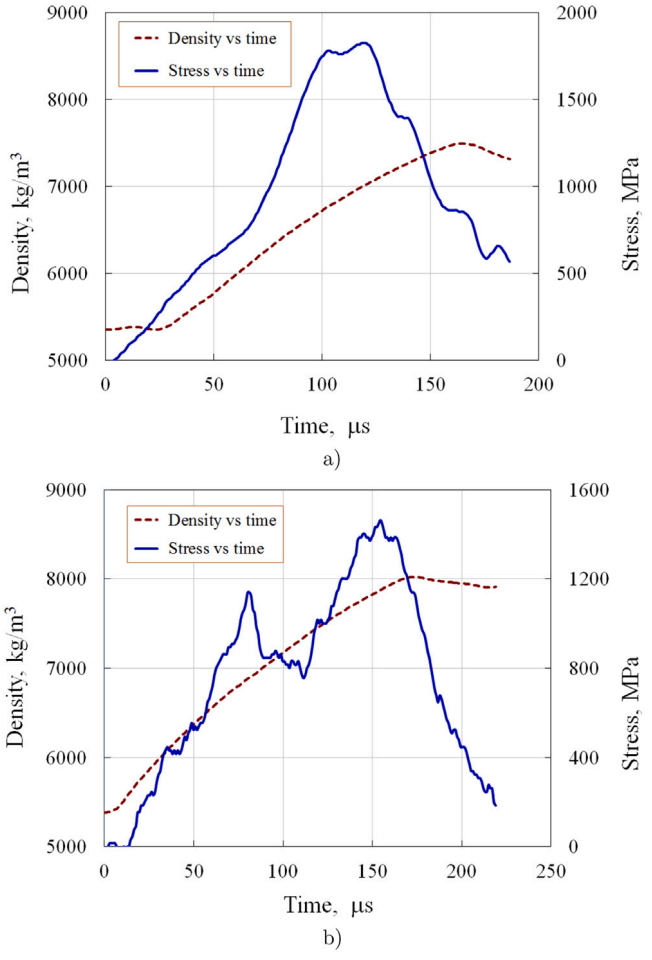

Fig. 5. Time history of the compaction process (density, stress) for the Fe+10%WC powder mixture at a temperature of 20 °C (a) and 300 °C (b).

physical properties of material of particles of formed medium. Preheating the specimen prior to compaction increases density due to further movement of the particles.

Micro-hardness of the surface of the compacts was measured using a standard micro-durometer along the diameter of the compacts with a step of 0.5 mm. For each sample, 5 series of measurements were carried out, the results of which were averaged. Standard statistical processing was performed and confidence intervals were determined at a significance level of $\alpha = 0.05$. The studies have shown that the density of all the produced compacts and their micro-hardness increase with pressing temperature (Table 2).

It has also been found, see Fig. 6a, that micro-hardness of compacts made of the Fe+5%WC mixture in the central part is higher than on the periphery of the specimens, possibly this phenomenon can be explained by the presence of friction between the powder material and the cartridge wall.

Substantial increase in micro-hardness of the compacts with higher content of WC can also be noted, as well as a more uniform distribution of micro-hardness along the diameter of the specimen (Fig. 6b). In the authors' opinion, this may be connected with a smaller value of the friction forces between the cartridge wall and the Fe+10%WC powder mixture because of a lower content of fine-dispersed iron powder as

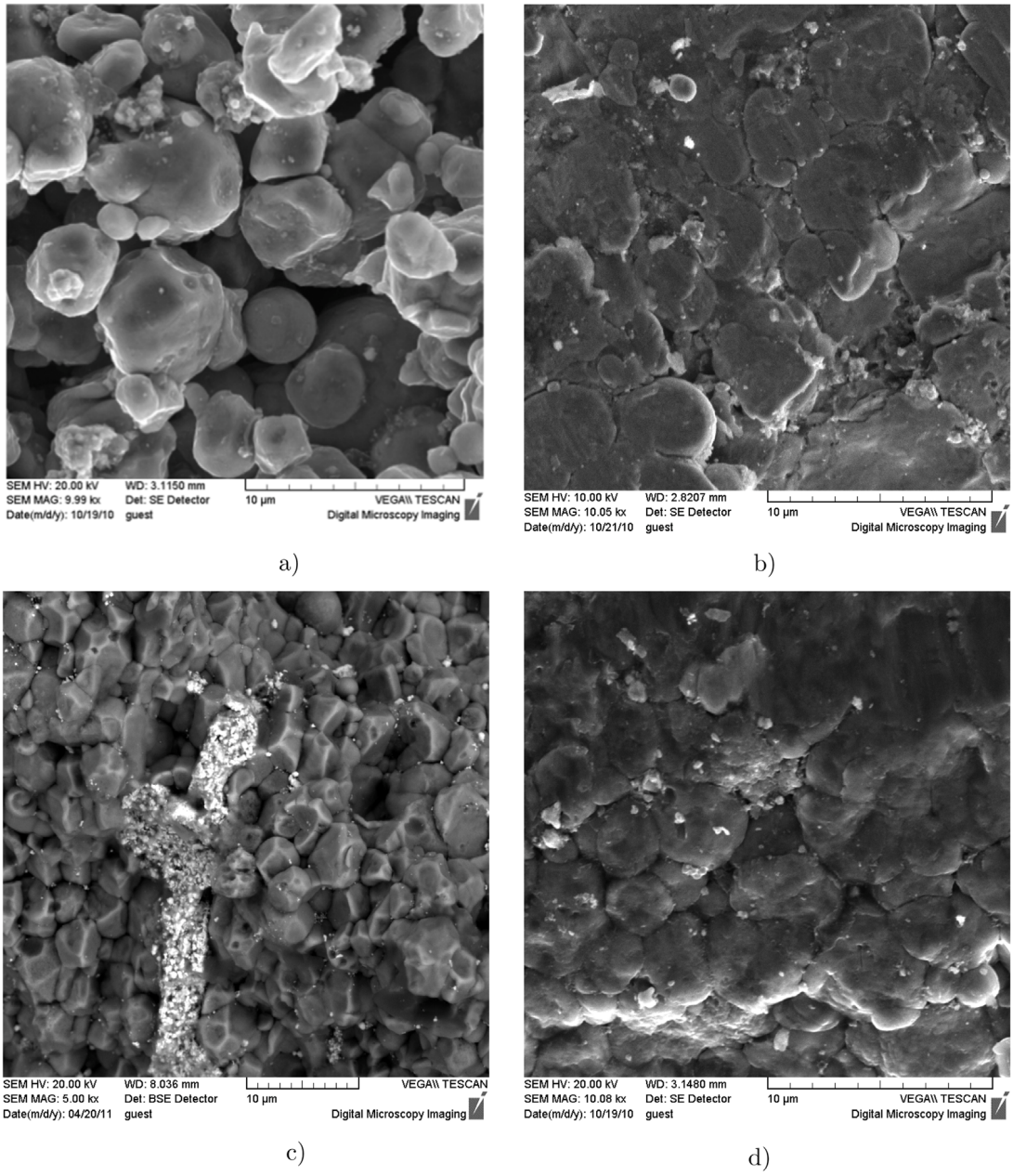

Fig. 6. The surface structure of the compacts obtained at a pressing temperature of 20 °C (a), +100 °C (b), +200 °C (c), +300 °C (d).

compared with the Fe+5%WC mixture. A detailed investigation of this issue will be a topic of special forthcoming studies.

The studies have also shown that an increase in the pressing temperature leads to an increase in the density of compacts (Table 2). The maximum relative density of the compact reached ~ 93% at a pressing temperature of 300 °C, whereas a minimum relative density of ~ 85% was observed in the compact obtained at a temperature of 20 °C.

Fig. 7 presents relative density and average micro-hardness of the compact surfaces as a function of pressing temperature for two initial powder mixtures. Compaction of the powder mixture under the applied loading is realized both due to relative motion of the particles and due to plastic deformation of the iron particles. The compacts with lower WC content and higher iron content are mostly compacted due to its high plastic properties (Fig. 7a). The increase of the density of the compacts almost linearly depends on pressing temperature. At the initial stage of pressing of the powder mixture, the main contribution into compaction is made by relative motion of the particles and by filling the gaps between big-size iron particles with smaller particles of WC. At the final stage of the pressing process, compaction is realized mainly due to plastic deformation of the iron particles. Exhaustion of plasticity of the particles of the studied powder mixture under the realized loading energy occurs earlier in the Fe+10%WC mixture, characterized by higher content of solid particles of WC, which predetermines a lower increase rate of micro-hardness with the pressing temperature as compared with the increase rate of micro-hardness of the Fe+5%WC mixture (Fig. 7b).

Tribological testing of the obtained compacts for wear was carried out at room temperature on a specialized test bench in the dry friction mode according to the ‘counterbody (rotating disk) — fixed specimen’ scheme (Fig. 3). The conditions of all tests were as follows: counterbody rotation speed of 70 revolutions per minute, sliding speed of 0.146 m/s, normal load in the contact zone of 25 kN. The total test time was 2 h, which corresponded to a total friction path of ~1051.2 m. The wear

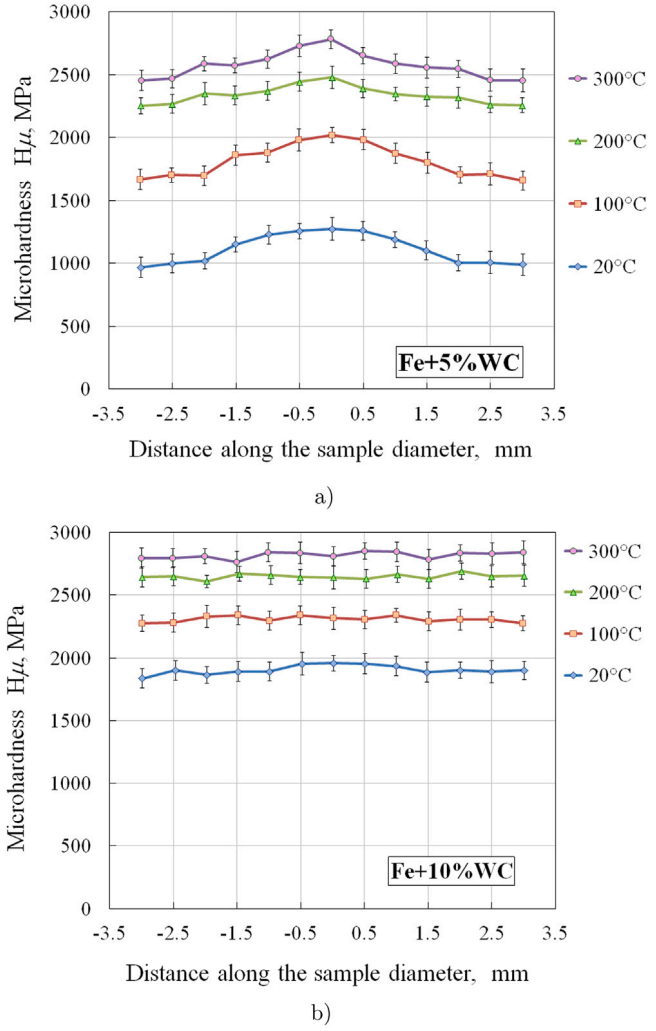

Fig. 7. Micro-hardness of compacts made of Fe+5%WC (a) and Fe+10%WC (b).

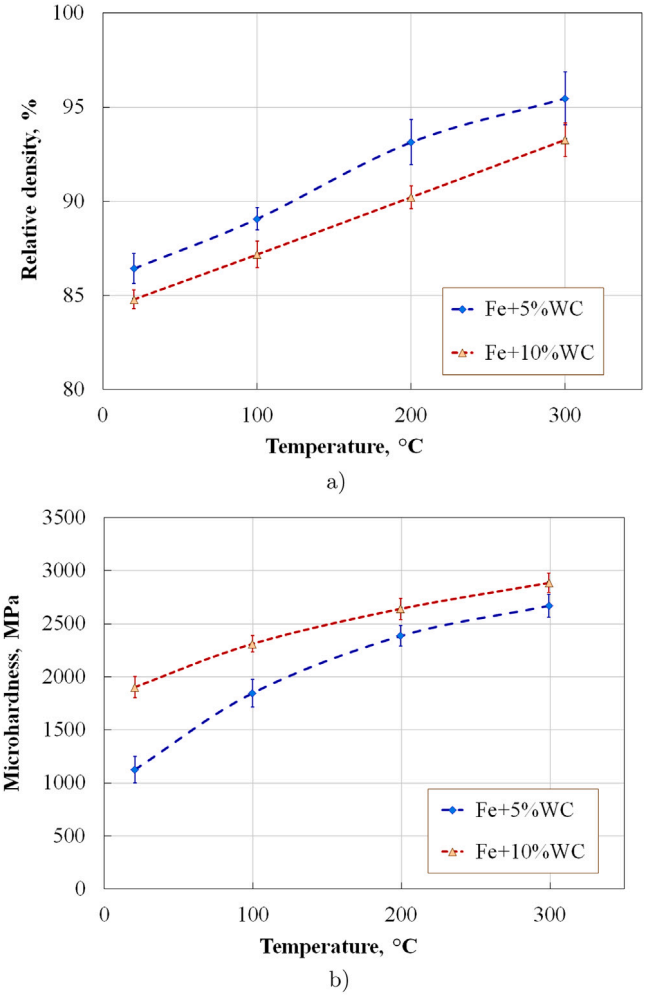

Fig. 8. Relative density (a) and average micro-hardness of the compact surfaces (b) as a function of pressing temperature.

resistance of the obtained compacts was evaluated every 30 min by the value of the mass loss of the specimen. Measurement of the mass loss of the samples during wear was carried out by weighing them on an Ohaus Explorer EX124 analytical scales with an accuracy of 0.1 mg. The results of studying wear resistance of the compacts produced from the two powder mixtures are summarized in Fig. 8.

The presented results testify to the fact that wear resistance of compacts depends on pressing temperature and concentration of WC nanopowder in the matrix of reduced iron. As was shown above, the value of micro-hardness of the compacts increases with pressing temperature, see Table 2. It can be seen in Fig. 9 that wear resistance of the compacts also increases, the contribution of the increase in pressing temperature for both powder compositions being more important than changes in the concentration of WC nanopowder. The studies have shown that wear resistance of the specimens of Fe+5%WC increased 1.9 times and that of the Fe+10%WC specimens increased 2.1 times at a pressing temperature of 300 °C as compared with pressing at ambient temperature, for the same loading conditions.

The results obtained in the experiments can be useful for equipping wear models in which a relationship is established between the surface roughness of the material and the friction and wear characteristics, similar to the models considered in [9,10].

4. Conclusions

We have been presented recent results on wear resistance of compact manufactured by modified Kolsky's method from powder materials. The main attention was paid to analysis of influence of pressing temperature and the nanopowder concentration. It has been found that increase in pressing temperature of the considered powder mixtures makes it possible to attain relative density of the produced compacts of over 90% at a pressing temperature of 300 °C.

Metallography of the structure of the produced compacts has shown that increase in pressing temperature leads to forming an improved fine-grained structure due to the increase in the juvenile surface area, and promotes activation of such surfaces and forming metallic bonding in the contact zone of the powder particles, which results in the increase in density and micro-hardness of the compacts. Besides, concentration of tungsten carbide plays an important role in increasing micro-hardness and wear resistance. It has been experimentally shown that maximal wear resistance is observed in the compacts with the mass fraction content of tungsten carbide (WC) equal to 10%, produced at a pressing temperature of 300 °C.

Summarizing, we can conclude that for higher WC concentration the compact structures are more uniform and have higher microhardness. This effect can be explained as follows. In the initial mixture, WC nanopowder particles fill the space between large Fe particles. The higher the concentration of WC particles, the lower the residual porosity in the initial mixture (even before pressing). After pulsed pressing,

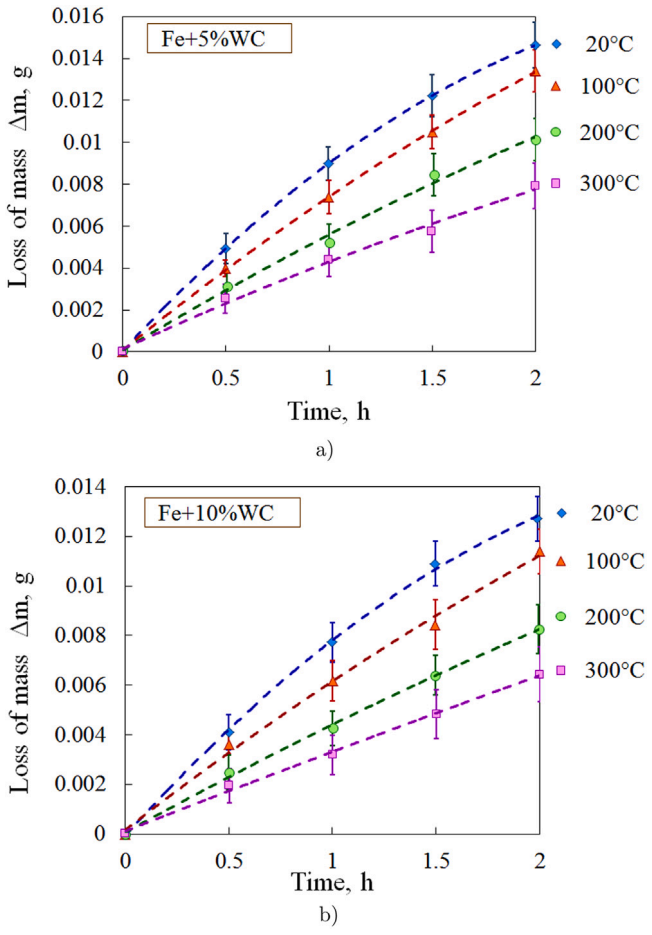

Fig. 9. Time histories of loss of mass of the compacts produced from powder mixtures of Fe+5%WC (a) and Fe+10%WC (b) when tested for friction.

a certain fraction of WC particles are fixed in the space between the Fe particles, and a part is embedded in the surface layer of Fe particles. The resulting structure resembles a mosaic one, which is based on Fe grains surrounded by WC particles. The hardness of WC is much higher than the hardness of iron, therefore, the higher the concentration of WC in the mixture, the higher the microhardness of the compact.

As the pressing temperature increases, the plasticity of the Fe particles increases. An increase in the density of compacts occurs mainly due to the fact that a larger number of WC particles are fixed in the surface layer of iron grains. The density of interparticle space (between Fe particles) filled only with WC particles increases with temperature. This leads to a noticeable increase in microhardness and, accordingly, to an increase in wear resistance. That is why with the increase of the compacting temperature we also have the increase of the wear resistance of obtained compacts.

CRediT authorship contribution statement

Anatoly M. Bragov: Conceptualization, Methodology, Writing - original draft. **Leonid A. Igumnov:** Supervision, Project administration, Funding acquisition. **Alexander Yu. Konstantinov:** Visualization, Investigation. **Andrey K. Lomunov:** Investigation, Validation. **Evgeny E. Rusin:** Investigation, Software, Visualization. **Victor A. Eremeyev:** Investigation, Visualization, Writing - review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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