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Tungsten Carbide Microparticles Introduction's Effect on Steel Hardness and Resistance to Local Impacts

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Abstract:
The article presents one of the technological methods for producing metallic materials through the micro- and nanoparticles interaction in order to increase their strength characteristics. For this, based on the scientific and technical literature review, the metal dispersed hardening technology in the centrifugal casting process was applied. To carry out disperse hardening, finely dispersed (1-5 μm) tungsten carbide particles were introduced into the metal melt during casting. The studies results of the samples' structure obtained using optical and electron microscopy. Tests were conducted in laboratory setup in which steel balls with the diameter of 6 mm and the mass of 1.05 g can be accelerated to speeds of more than 600 m/s. The samples obtained, saturated with refractory microparticles of tungsten carbide, showed high hardness and resistance to local impact characteristics with the stable type of fracture.

***Keywords**: casting, micro and nanoparticles, tungsten carbide, crystallization, hardness, fracture.*

Introduction

One of the most important tasks in metallurgy and mechanical engineering is the new materials development and their implementation, as well as material-saving technologies. Nowadays, micro- and nanocomposite materials are being used increasingly. Nanomaterials include materials containing structural elements that do not exceed 100 μm in at least one dimension and have qualitatively new properties: functional and operational. This is because the nanoelements (nanopowders, nanotubes, nanofilms) that are part of the material have large atoms fraction located on the surface. The surface atoms bonds are partially uncompensated, which can be emerged in number of nanoparticles' unique physical and chemical chrateristics. New materials created using nanotechnologies or something close to them can be very useful in those industries where cost is secondary factor, for example, in aviation, astronautics, guarding people's lives from various threats, in particular, personal protective equipment (bulletproof vests for example), designed to ensure human safety when exposed to cold (blade) or firearms.

For successful military operations, high-strength steel may be widely considered; however, the structural steels such as low-strength steels are used in the building, automobile and industrial applications. For instance, the tallest structures are constructed using structural steel due to its constructability. High-strength and low-strength steel plates are predominantly used as civil, aerospace and military protective

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structures. The idea of using these plates is to protect the personnel against accidental loads, terrorist attacks or international peace keeping operations. The material should be able to sustain the strain gradients without cracking up (Bhat, 1985). This is possible only when the ductility, which is an important quality of good armour, increases with strain rate. High hardness and impedance of the armour material can induce high stresses on the projectile which can absorb its energy on itself. The ballistic performance increases with the increase in the thickness of the steel with higher hardness. This is valid up to some value of such thickness. The ductile interlayer addition leads to the improvement in the given performance. Although the increase in the steel's hardness improved its ballistic behaviour, the steel specimens having either 50 or 60 HRC were broken in brittle manner rather than perforation by the projectiles (Demir et al., 2008). Hardness levels in steel plates played important role in the ballistic performance. When the steel plates's hardness increased, the penetration and projectile propagation ability decreased significantly (Übeyli et al., 2007).

Gooch et al. (2007) observed that as the steel plates's hardness increased, the ballistic limit also increased against AP projectiles. The detailed literature survey has been carried out on the target, and projectiles in this study have been carefully identified (Borvik et al., 2009; Brian, 1996; Dikshit, 1998; Goldsmith and Finnegan, 1986; Gupta and Madhu, 1997; Iqbal et al., 2016; Jena et al., 2010; Kilic and Ekici, 2013; Pritti et al., 1997; Showalter et al., 2007).

The target material and impactor have been identified keeping in view the application in construction and automobile industry, personnel's current requirement and lack of literature studies. The rapid technological development and increased number of wars in the 19th century led to development of sophisticated weapons. The light-weight and high-strength metals had always been the primary requirement for the weapon as well as armour industries; however, their demand increased considerably after World War II. The selection of suitable armour materials for defence applications is very crucial in order to design military vehicles, structural occupancy and military bunkers. The ideal material should possess the lowest areal density, high ductility and high strength. The number of various material systems can be considered in this perspective. However, high-strength steel still seems to be an ideal material for armour applications due to high strength and superior mechanical properties. Also, the investigations on armour steel plates against normal and oblique impact by different penetrators and fragments with computer help is interesting (Borvik et al., 2009; Buchar et al., 2002; Iqbal et al., 2015, 2017).

While creating the new generation of body armor, the main parameters are protection, the vest 's weight and the last one is the cost. In this regard, research aimed at reducing the products' mass while protection maintaining the level is most relevant. It should be noted that modern combined metal fabric bulletproof vests are designed basing on the new concept of metal armor panel penetration with increased diameter the "plate" (spall) formation, which can be successfully stopped by the fabric bag made from special high-strength fibers. Thus, when creating new promising steel grades for the bulletproof vests manufacture, we should strive to obtain given breakdown - spallation mechanism (Hazell, 2006).

Promising direction in the composite materials production with high mechanical characteristics could be the carbides, oxides or nitride particles dispersion into metals (Chumanov et al., 2010; Komshukov et al., 2010).

Such materials examples are carbide steels, hard alloys, and dispersion-hardened materials (Allen et al., 2001, Kiviö et al., 2016, Watanabe et al., 2011). Dispersion-hardened materials are metal materials (mainly alloys), hardened by dispersed particles of refractory compounds (oxides, carbides, nitrides, etc.) that do not dissolve and do not coagulate in the metal matrix (base) at high operating temperatures. The maximum hardening effect is achieved with sufficiently small size of the particles in the strengthen-

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ing phase (0.01-0.05 μm), their uniform distribution in the material structure and the optimal distance between the particles. To the greater or lesser extent, introduced particles interact with the melt, and the characteristics acquired by the material depend on the interaction degree, as well as on the chemical reactions products of their interaction.

One of the directions to control the dispersed particles location during metal crystallization is the disperse-hardening particles introduction into the metal during centrifugal casting (Chumanov et al., 2011).

Conducting experiments

Using steel mark 1020 as an example, the influence on the strength characteristics of entering into the crystallizing melt during steel casting at the centrifugal casting unit of tungsten carbide micro- and nanoparticles, was investigated. The introduced particles serve as crystallization centers, accelerate the crystallization process, grind grain and increase mechanical properties. In addition, tungsten carbide particles have high hardness; therefore, in the blanks structure, they serve as reinforcing elements that strengthen the structure. Also, to give the experimental samples the necessary configuration, the castings forging was carried out according to the scheme proposed by the authors. This technology was taken as the basis of this work.

Samples were obtained by melting in an induction furnace, then casting was carried out in a horizontal type centrifugal casting plant, with mold speed of 800 rpm. Casting continued for 15-20 seconds. The temperature of the metal melt was 1680-1720 °C. Reinforcing particles were introduced using screw type dispenser. The particles size was 1-3 μm. Total 2 castings with different concentrations of reinforcing particles were obtained. Casting 1 - standard, without the dispersed particles introduction; casting 2 - with reinforcing particles concentration WC = 0.1 wt. % The resulting castings had the following dimensions: outer diameter 185 mm, inner diameter 145 mm, length 180 mm (Fig. 1).

Steel and alloys used in the manufacture of machines critical parts and constructions must have fine-grained structure, as in this case they have higher complex of mechanical characteristics compared with steels having coarse-grained structure.

In this paper, we consider one of the technological methods for the metals manufacture (matrix melt) with active micro- and nanoparticles, contributing to an increase in their strength properties and noticeable decrease in the obtaining the material cost.

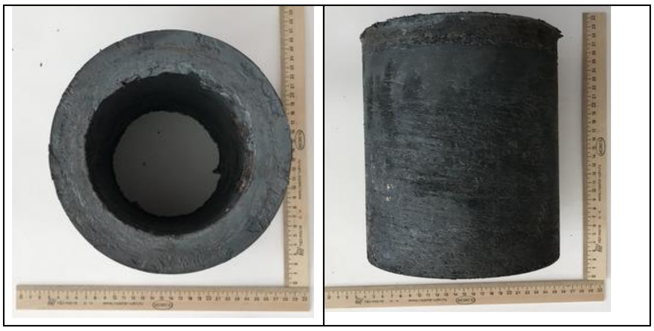

Fig. 1. Appearance of castings

After casting, the samples were subject to deformation (forging) at the temperature of 800 °C. The scheme of samples' obtaining and deformation is shown in Fig. 2.

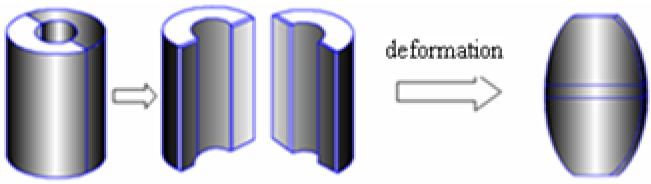

Fig. 2. Samples' obtaining and deformation scheme

During deformation, the wall thickness of the casting reduced from 20 mm to 5 mm. After deformation, the obtained samples were ground and polished to conduct microstructure studies using the optical and electron microscope.

The chemical composition of the obtained castings was studied using an MCA II emission spectrometer. The study results are presented in Table 1.

Table 1. The chemical composition of the obtained castings

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Casting number	The content of elements, mass. %							
	C	Si	Mn	P	S	Cu	W	Fe
1	0.21	0.24	0.39	0.034	0.028	0.12	0.01	Basis
2	0.19	0.25	0.36	0.033	0.028	0.11	0.05	Basis

Investigation of microstructure

The structure of the experimental ingots was studied using an optical microscope Axio Observer.D1m. To reveal the structure, polished samples were etched with a 5-% solution of nitric acid in alcohol. The image analysis system for metallurgical tasks and quality control "ThixometPRO" was used. From these images of the Thixomet® image analyzer, it can be concluded that all samples structure has the direction perpendicular to the forging. The structure of casting No. 1 is ferrite with small pearlite grains inclusions (Fig. 3a) located in the interdendritic gap. The structure of casting No. 2, is basically the same as in sample No. 1 (Fig. 3b), with difference in the slightly smaller size of the dendritic cell. Studies using a JEOL JSM 6460-LV electron scanning microscope made it possible to determine that the introduced WC particles are micro- and nanoscale, in some cases less than 0.5 μm (Fig. 4).

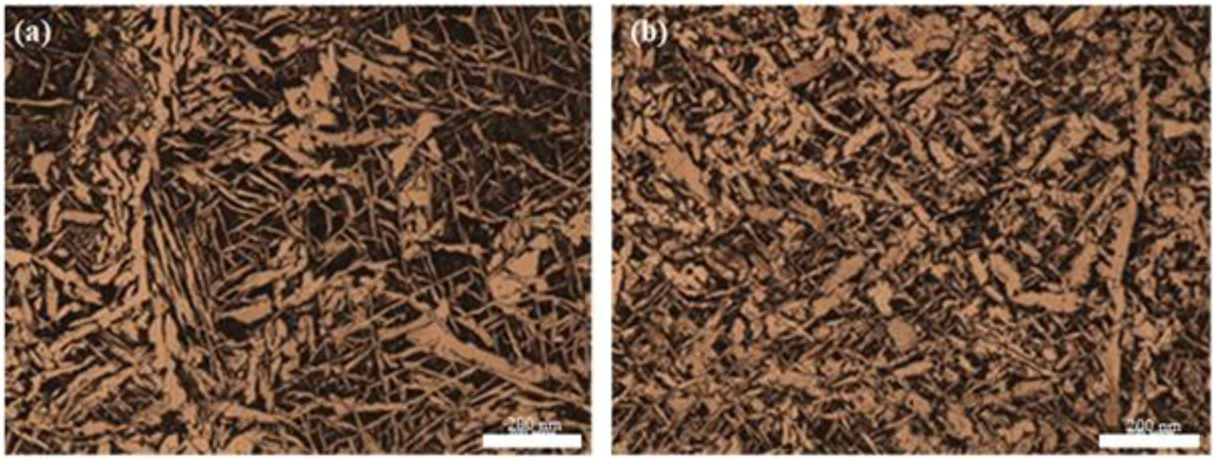

Fig. 3 Microstructure of the obtained castings: a - No. 1, b - No. 2

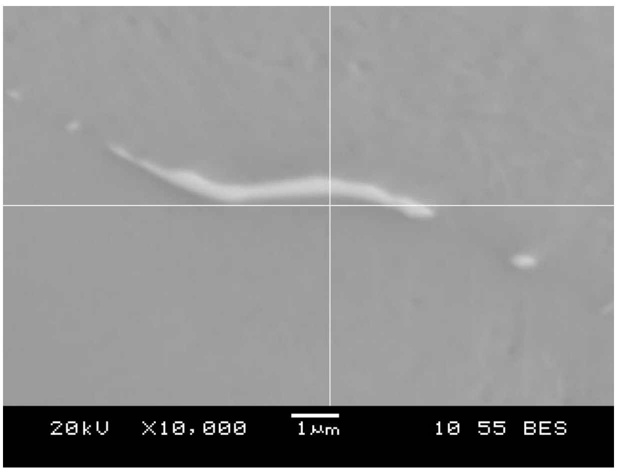

Fig. 4. WC particles in the metal structure (sample 2), × 10000

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Investigation of hardness and resistance to local impacts

In order to give the samples high hardness values, normalization was carried out at the temperature of 850-870 °C. When determining Brinell hardness (HB) with a 10 mm diameter ball, a load (30 kN) was applied using an INSTRON 5882 testing machine, the load application speed was 1.25 kN/min. The prints diameters were measured in two mutually perpendicular directions using an optical microscope with 0.05 mm the division. It showed that the sample made of steel grade 1020 with introduced refractory particles has a higher hardness compared to standard sample 1. Breakdown tests were carried out in a laboratory where steel balls with 6 mm diameter and 1.05 g mass can accelerate to speeds of more than 600 m/s (Sapozhnikov et al., 2013).

In this design, it is proposed to use the gases energy of standard mounting cartridges (series D and K), available on the market. The energy of these cartridges varies from 300 to 1000 J, which is quite enough to accelerate steel spherical impactors with 8 mm diameter (mass 2.2 g) with the speeds noted above. Serial production of mounting cartridges allows to obtain high stability in throwing speeds, and fixed barrel length (150 mm) - to provide compactness to the booster block and the entire stand as a whole. Mounting cartridges have lateral ignition, which requires the impact striker manufacture with needle offset from the axis by 4 mm distance. The shutter is spring, mechanical with manual cocking; the shutter can be released remotely. Since the spherical impactor has gap of about 50 μm in the barrel, it is necessary to use light wad made from polyethylene (weight about 0.25 g), which prevents the gases breakthrough into the gap and increases the coefficient of cartridge utilization energy.

Table 2. The measuring hardness results before and after heat treatment

Sample number	Diameter of the print, mm	Hardness, HB
1	5.35	129
	5.40	126
2	4.60	170
	4.55	174

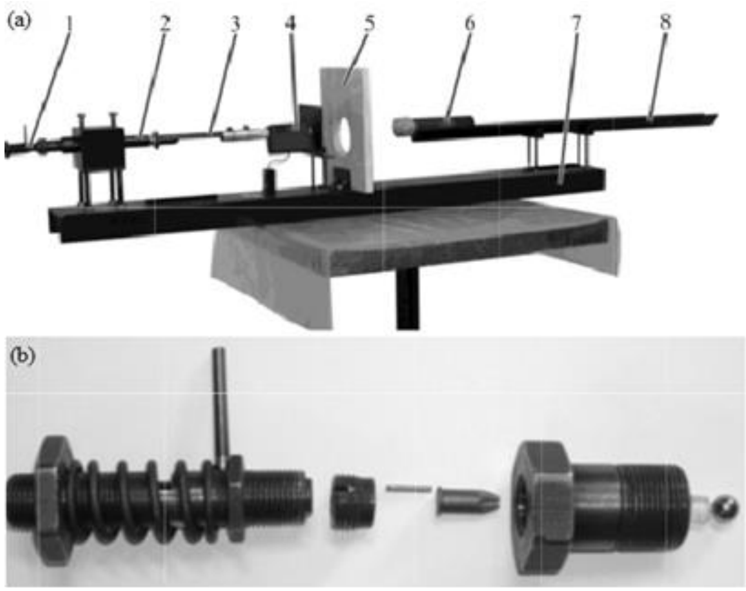

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Fig. 5. Desktop overclocking stand (protective cover removed): a - 1 - shutter; 2 - trunk; 3 - gas outlet pipe; 4 - initial speed meter (chronograph); 5 - stand for the target; 6 - friction trap; 7 - base; 8 - guide traps; b - shutter and breech with wad and projectile

By changing the cartridge energy intensity or moving the wad with striker closer to the barrel cut, you can adjust the departure speed. The hammer initial velocity measurement is made by standard digital chronograph type S06 with an error of not more than 1 m/s based on 70 mm. To prevent contamination of the optical chronograph sensors by products of gunpowder incomplete combustion, the chronograph is removed from the barrel at 15 sm distance using gas exhaust tube 3. The target is set near the chronograph at 10-20 cm distance. As a result of the obstacle breakdown, the indenter speed decreases, it falls into the trap 6 , which is steel tube with fabric packing, and stops, giving it residual impulse. The trap is displaced by certain distance, overcoming the friction forces with the guide - support 8. This displacement is measured (error not more than 0.5 mm) for subsequent conversion to the striker residual velocity according to the calibration dependence. The average error in measuring the residual velocity in this way does not exceed 10 m/s (possible non-parallelism of the velocity vector ν and the guide axis, friction coefficient fluctuations along the guide length, trap oscillations during movement, etc.).

Previously, special grips were developed and manufactured for fastening the studied metal samples for breakdown testing.Also, to obtain valid data, the experimental plates thickness was reduced to 2.35 mm by mechanical removal of the metal layer. This was due to the test bench design and characteristics.

The tests' parameters and the results obtained during them are presented in Table 3. During the tests, the speed of the projectile in contact with the test materials, the trap displacement, the fragments mass in the event of failure, and the breakout type were measured. The test results are presented in Fig. 6, where the numbers correspond to the test number in Table 3. According to the external evaluation of the test results, it can be noted that the refractory particles introduction into the metal matrix increases the material resistance to local impacts (in a number of tests at the same speed of the impactor breakage of plate No. 2 isn't happening).

Based on the obtained data, ballistic breakdown curves were constructed (Fig. 7), where the speed values of the steel ball are located on the abscissa axis, and the residual velocity of the tube formed as ball impact result is located on the ordinate axis.

Table 3. Initial data and experimental results

No.	Speed of projectile (m/s)	Trap offset (mm)	Mass of fragments (g)	Breakdown type
Sample 1				
1	840	206	0.45	through
2	763	81	0.42	through
3	668	81	0.45	through
4	640	82	0.41	through
5	579	36	0.37	through
6	563	24	0.41	through
Sample 2				
7	495	0	0.41	projectile stuck
8	571	47	0.40	through
9	466	0	-	projectile stuck
10	514	30	0.42	through

11	450	0	-	projectile stuck
12	720	84	0.44	through
13	505	0	0.44	projectile stuck

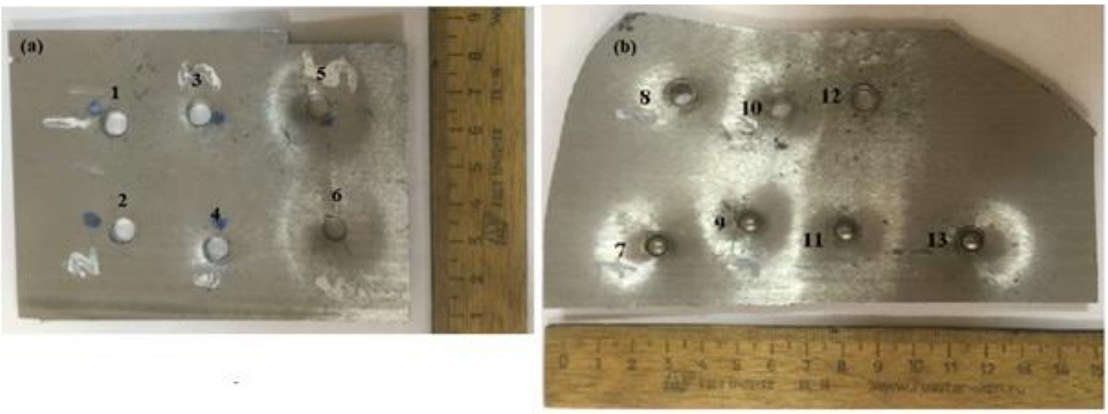

Fig. 6. Experimental samples' appearance after tests at the bench: a - No. 1, b - No. 2

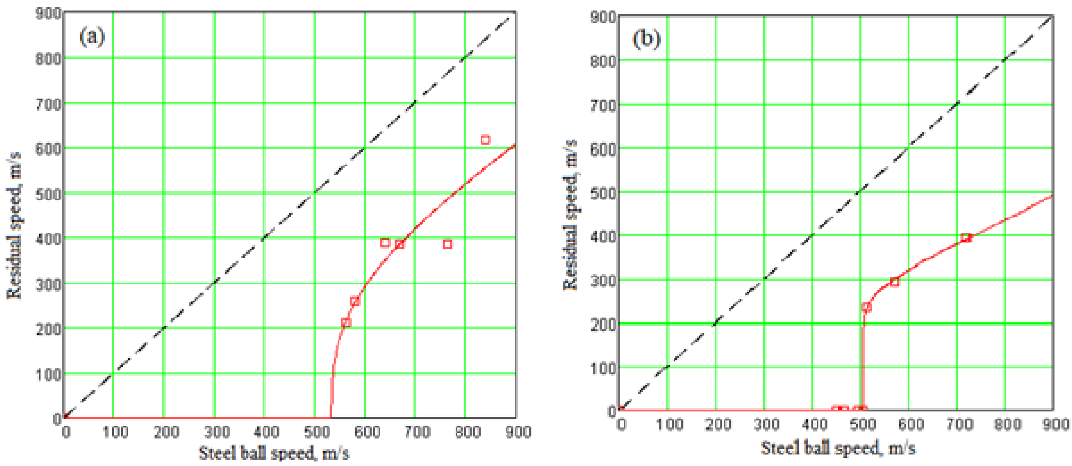

Fig. 7. Ballistic breakdown curves: a - No. 1, b - No. 2

Conclusion

When comparing the residual velocity (speed of the flying plug) with impactor speeds of 700-900 m/s in the case of a plate, which has reinforcing particles, this indicator is lower, and that indicates the increase in ballistic resistance of this material type and the resistance increase to local impacts. Thus, a sample saturated with tungsten carbide refractory microparticles has higher hardness characteristics and resistance to local impacts with a stable spall fracture type compared to ordinary steel mark 1020 sample. The results will be used in further studies, including mathematical modeling of local impact, the construction of mathematical models and testing the impact of the proposed experimental materials with firearms.

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