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Increasing the durability of drill bit teeth by changing its manufacturing technology

Javokhir Toshov[1, a], *Doniyor Fozilov*[2, b], *Kassym Yelemessov*[3, c], *Ulugbek Ruziev*[2, d], *Dovudjon Abdullayev*[2, e], *Dinara Baskanbayeva*[3, f, *], *Lala Bekirova*[4, g]

[1] Tashkent State Technical University, 2, University st., Tashkent, 100095, Republic of Uzbekistan
[2] JSC “Scientific and Production Association” Almalyk MMC”, 1 V. Gaidarova st., Chirchik, 111700, Republic of Uzbekistan
[3] K.I. Satbayev Kazakh National Research Technical University, 2 Satbaev st., Almaty, 050013, Republic of Kazakhstan
[4] Azerbaijan State Oil and Industry University, 34 Azadliq Ave., Baku, AZ1010, Azerbaijan

[a] https://orcid.org/0000-0003-4278-1557, j.toshov@tdtu.uz; [b] https://orcid.org/0009-0005-6362-8326, fozilovdoniyor81@gmail.com;
[c] https://orcid.org/0000-0001-6168-2787, k.yelemessov@satbayev.university; [d] https://orcid.org/0009-0008-2371-3085, u.ruziev@agmk.uz;
[e] https://orcid.org/0009-0005-6362-8326, dn.abdullaev@agmk.uz; [f] https://orcid.org/0000-0003-1688-0666, d.baskanbayeva@satbayev.university;
[g] https://orcid.org/0000-0003-0584-7916, lala.bakirova@asoiu.edu.az

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ABSTRACT

Introduction. The development of the mining industry requires increasing the durability and safe tool performance life. For bits of mining drilling machines, this problem is often solved by improving the material of the teeth of these bits. The paper presents the results of a study on the development of a technology for the manufacture of hard-alloy drill bits with increased wear resistance and testing of prototypes when drilling hard rocks. Changes in technology have led to changes in the shape of the tooth. Also, purer tungsten powder was used as the initial component. **Research methods.** The paper studies carbide teeth of bits manufactured at *JSC Almalyk Mining and Metallurgical Combine* using standard and modified technology. Its structure and chemical composition were studied. **Results and discussion.** New methods for performing technological operations for the manufacture of carbide teeth (pins) and steel pin bits are developed and mastered. Tungsten-cobalt teeth were manufactured using *VK10KS* (90 % *W*; 10 % *Co*) hard alloy, produced using tungsten carbide powder synthesized by carbidization of purified tungsten powder. The shape of the tooth surface was changed from ballistic to semi-ballistic. Metallic cobalt powder was used as a binder. Pin bits of the *KNSh40×25* type are made of *0.35 C-Cr-Mn-Si* steel. Tests of experimental bits were carried out at several mines, as a result of which its suitability for drilling rocks with a hardness of *f* = 14–18 was established. The results of industrial operation showed that the durability of the teeth of bits manufactured by *JSC Almalyk Mining and Metallurgical Combine* is not significantly inferior to bits from European manufacturers. At the same time, the cost of such bits is several times lower.

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Introduction

The mining industry in Central Asia is actively developing due to the presence of rich natural resources. Central Asian states, including Uzbekistan, Kazakhstan, Tajikistan, Kyrgyzstan and Turkmenistan, are actively developing the mining industry in an effort to increase production and attract foreign investment [1]. One of the key areas of the mining industry development is the extraction and the processing of rare

*** Corresponding author**
Baskanbayeva Dinara D., Ph.D. (Engineering), Deputy Director
K.I. Satbayev Kazakh National Research Technical University,
2 Satbaev st.,
050013, Almaty, Republic of Kazakhstan
Tel.: +7 701 861 5162, **e-mail:** d.baskanbayeva@satbayev.university

earth metals. Rare earth metals play an important role in the manufacture of high-tech products, such as electronics, batteries and renewable energy equipment [2–5]. Increasing the mineral extraction requires active improvement of both equipment and machinery, as well as extraction tools.

Rotary-percussive drilling is a combined type of drilling that combines rock cutting with the application of percussive loads. In this type of drilling, the rock cutting tool is subjected to torque, static feed force and impacts of a certain frequency and force. In some geological conditions, rotary-percussive drilling turns out to be more productive than rotary and percussive drilling separately. This explains its wide application in various mining operations [6, 7].

Efficient rock destruction during rotary-percussive drilling with carbide bits is achieved by an optimal selection of the carbide composition, the tool size, the geometry of cutters, its location along the bit face, the well-organised flushing system and properly calculated parameters of the drilling mode [8–10].

In pin drills, hard alloys are used as the material for the cutting teeth, usually tungsten-cobalt alloys *VK6* (94 %*W*; 6 % *Co*) and *VK8 (92 %W; 8 % Co)*. These carbide materials have proven to be reliable and relatively inexpensive to use. Bits of such type can be exploited in the rocks up to the ninth category of drillability [11].

Bit wear resistance in operation depends on geological and technical drilling conditions: hardness, abrasiveness, fracture density, discontinuity of rocks; rotation speed, diameter of the bit and axial load; a depth and curvature of the borehole, serviceability of the drilling machine [12–15]. However, the hardness and bending strength of carbide cutters, as well as the quality of manufacturing and the assembly of the pin bit, are of decisive importance.

A significant share of such tools is produced in European countries and has a high cost. Within the framework of the *Almalyk MMC JSC* enterprise (Uzbekistan), rock-cutting bits are produced at a significantly lower cost. At the same time, the resistance and durability of such bits are lower than those of European analogues.

The purpose of this work is to increase the durability of drill bit teeth by improving the manufacturing technology of this tool

Research Methodology

This work was carried out in three stages. At the first stage, an analysis of the causes of the destruction of the bits manufactured by *Almalyk Mining and Metallurgical Company JSC* was carried out. At the second stage, based on the results obtained, the technology of bit teeth manufacturing was changed, and the samples, obtained by the new technology, were investigated. At the third stage, the comparative testing of bit samples manufactured using the improved technology and European analogues of the *Atlas Copco* company (Sweden) were carried out.

The research work was performed on the basis of the Scientific and Production Association for the production of rare metals and hard alloys of the *Almalyk Mining and Metallurgical Company JSC* (*NPO AGMK*). The research was focused on the development of the technology to manufacture the *KNSh* 40×25 mm type drill bits with seven inserted pins-tooths that are similar to *Atlas Copco* drill bits (Sweden). Prototype bits were manufactured using tungsten-cobalt alloy carbide teeth. The teeth were produced at *NPO AGMK*.

Structural studies were carried out, using a *Carl Zeiss Axio Observer Z1m* light microscope and a *Carl Zeiss EVO 50 XVP* scanning electron microscope (*Jena*, Germany). The phase composition was studied using an *ARL X'TRA* X-ray diffractometer (*Thermo Fisher Scientific*, *Waltham*, MA, USA) in the *CuK*α radiation. For metallographic analysis of the bit tooth surface, the visual-optical method was employed, using a *Carl Zeiss Axio Observer A1m* microscope.

Results and Discussion

Determination of the causes of destruction of the teeth of bits manufactured using standard technology

The experimental testing of the first samples of *KNSh* 40×25 mm roller cones was characterised by low wear resistance during penetration, compared to that of the imported samples produced by *Atlas Copco* (Sweden). Fig. 1 shows a sample of *KNSh* 40×25 mm bit after testing for penetrating granite to a drilling depth of 18 cm (*a*), and an enlarged image of the porous surface of the tooth with depressions forming the so-called "*reptile skin*" surface (*b*).

a

b

Fig. 1. Seven-cone drill bit type *KNSh40×25* manufactured by *NPO*, after operational tests during drilling of granite rock; drilling depth 18 cm (*a*); the condition of the surfaces of the teeth of the crown, characterized by porosity with depressions known as the formation of the "*reptile skin*" surface (*b*)

Fig. 2 presents an enlarged image of the surface area at the boundary of the tooth wear area with the tooth surface before wear, which shows that along the boundary there is a separation of whole clusters of grains of the hard *VK (WC-Co)* alloy as a result of wear.

The "*reptile skin*" type surface is the result of maximum tensile stresses occurring at individual points of contact with the asperity of the rock.

Fig. 3 provides a schematic example, explaining the mechanism of crack formation on the tooth surface. According to the source, a protruding part of the rock is pressed into the tooth surface, creating localised stress on its surface. When this procedure is repeated several times, small cracks aggregate, eventually forming a "*reptile skin*" structure.

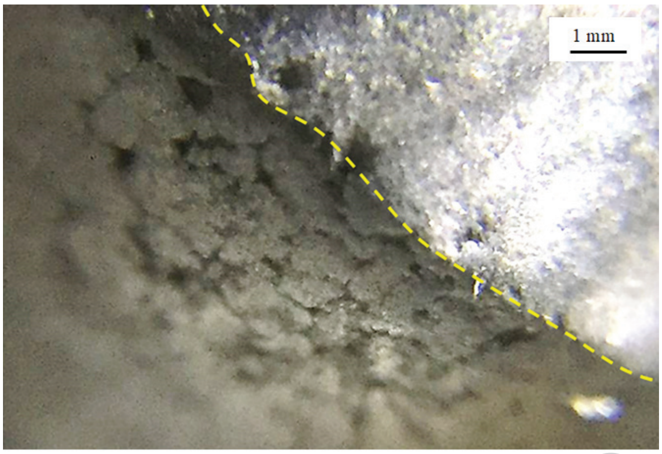


Fig. 2. Cross-section of the boundary of the surface of the tooth wear area with the tooth surface before wear: left – original surface; right – surface as a result of wear

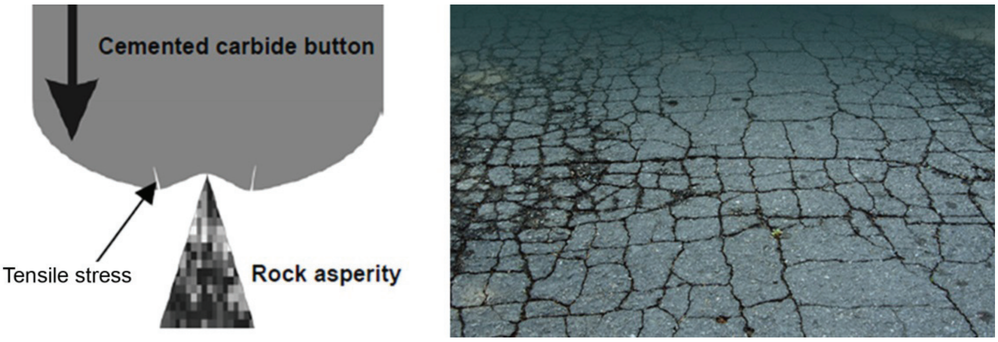


Fig. 3. The mechanism of formation of "*reptile skin*"

In order to establish the reasons for the low wear resistance of the experimental bits, the *AGMK NPO* carried out the research, aimed at developing optimal methods for manufacturing tungsten-cobalt teeth, its firm fixation in the bit grooves and improving the technology of its assembly. According to literature sources [16, 17], the materials can be separated from the surfaces of carbide teeth in several ways:

- grinding of grains of the *VK (W-Co)* hard alloy and separation of fragments;
- separation of whole grains or parts of grains that lose its ability to be retained in the structure;
- grinding the mixture: *VK (W-Co)* hard alloy /rock binder and separation of fragments;
- tribochemical wear, scraping off corroded or oxidised surface layers of *VK (W-Co)* hard alloy;
- separation of composite fragments of *VK (W-Co)* grain groups together with the binder.

A study of the microstructure of tungsten-cobalt teeth samples of the first experimental batches showed that one of the reasons for the formation of a porous structure with depressions, prone to the formation of pits, cracks and chips, when the teeth are exposed to roughness of rocks, was the large size of tungsten carbide grains. The large size of tungsten grains is obtained as a result of using conventional metallic tungsten powder containing undesirable impurities of calcium, silicon, iron and Sulphur.

Fig. 4 demonstrates the microstructure of a conventional sample of hard *VK10* (90 %*W*; 10 % *Co*) alloy, the elemental composition of which revealed a significant content of impurities that negatively affect the physical and mechanical properties of the alloy (Fig. 5).

Fig. 6 shows the microstructure of the junction surface of a sample of conventional hard alloy *VK10* (90 %*W*; 10 % *Co*). The hard alloy can be seen to be characterised by the presence of areas of inhomogeneity in the form of clusters of large spherical formations, as well as clearly foreign particles, exposed on the fracture surface of the *VK10* (90 %*W*; 10 % *Co*) sample (Fig. 7). This explains the cause of the fracture.

The areas of inhomogeneity and the presence of grains of foreign impurities negatively influence the bending strength, hardness, impact toughness and other physical and mechanical properties of the hard alloy *VK10* (90 %*W*; 10 % *Co*), which should ultimately determine the operational wear resistance of manufactured carbide teeth.

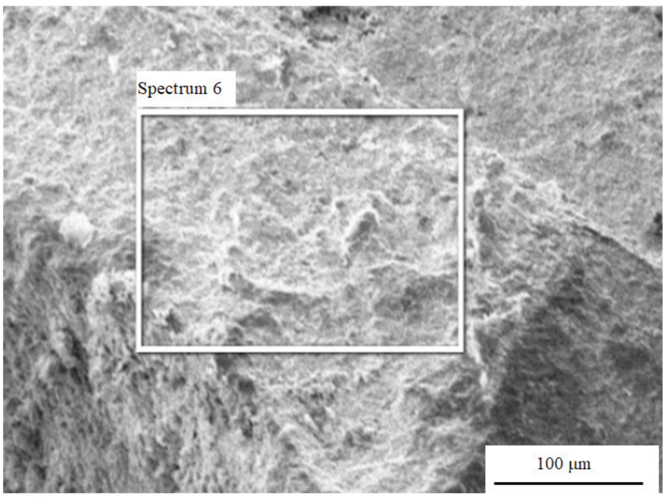


Fig. 4. Morphological features of the microstructure of a conventional sample of hard alloy *VK10* (90 %*W*; 10 % *Co*)

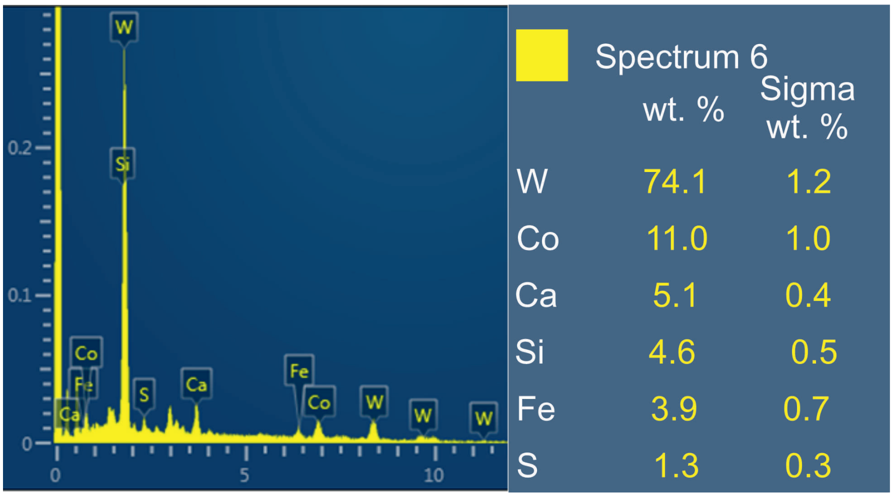


Fig. 5. Results of elemental analysis of a section of the microstructure of a sample of conventional hard alloy *VK10* (90 %*W*; 10 % *Co*)

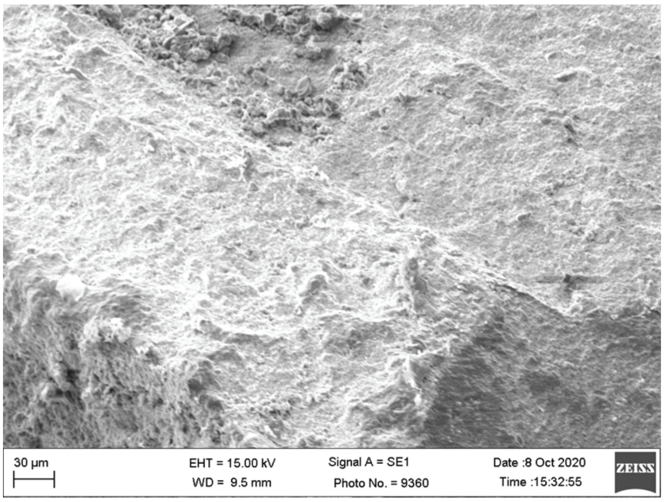


Fig. 6. Cleavage surface of a sample of conventional hard alloy *VK10* (90 %*W*; 10 % *Co*)

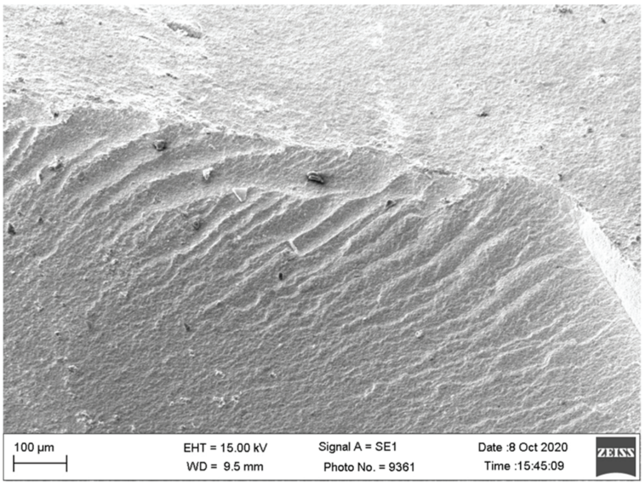


Fig. 7. Fracture surface of a sample of conventional hard alloy *VK10* (90 %*W*; 10 % *Co*)

Improvement of the technology for producing bit teeth

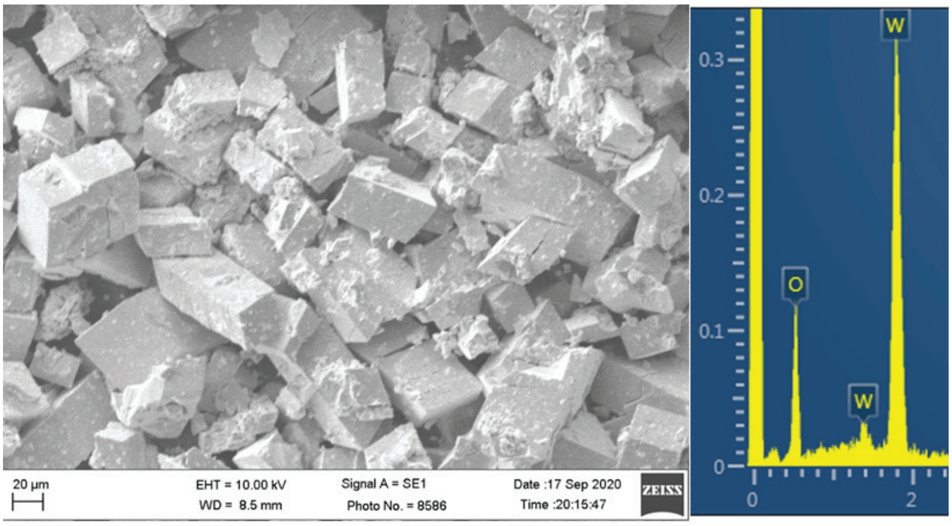
To achieve high purity and homogeneity of the *VK10* (90 %*W*; 10 % *Co*) alloy for drilling bit teeth, the technological parameters for obtaining high-purity tungsten metal powder were developed and tested.

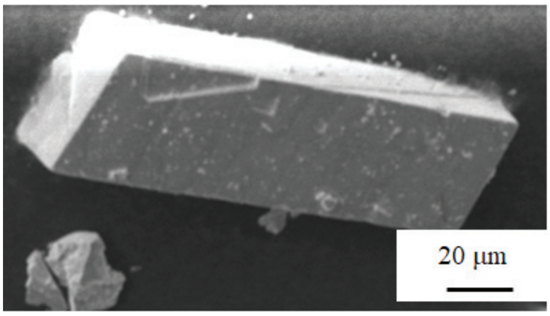
For this purpose, the technology of obtaining initial tungsten trioxide of high purity was developed. The description of the technology was provided in earlier works of the authors [18, 19]. Fig. 8 presents a micrograph of the tungsten trioxide powder, consisting of homogeneous prismatic crystals. The elemental composition is characterised by the presence of tungsten and oxygen. The ratio of these elements corresponds to the stoichiometry of the trioxide.

Fig. 9 shows a micrograph of crystals of the tungsten metal powder, obtained from pure tungsten trioxide. Fig. 9 provides the results of the elemental analysis of the crystals of the obtained tungsten metal powder.

Fig. 10 shows the results of the elemental analysis of a sample of synthesised pure metallic tungsten powder, confirming its high purity.

Pure metallic tungsten powder was used to obtain tungsten carbide by the method of carbidization, using graphite powder according to the technology of *NPO AGMK*. The pure metallic tungsten powder with the ***W*** content of more than 99.80 %, i.e. corresponding to the *KS* grade, was used. The reduction was carried out according to the mode of obtaining its carbide powder, with an average *Fischer* grain size





Element	wt. %	Sigma wt. %
O	18.81	1.01
W	81.19	1.01
Total	100.00	

Fig. 8. Tungsten trioxide powder crystals; results of elemental analysis of tungsten trioxide powder

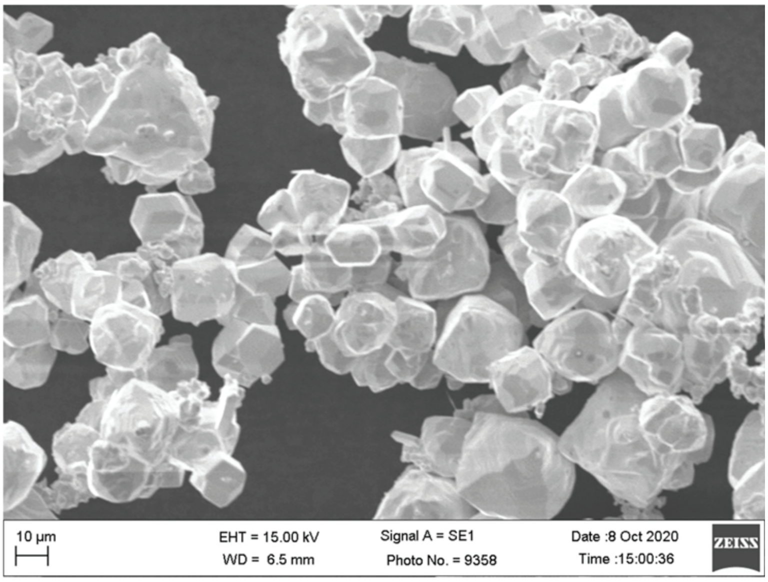
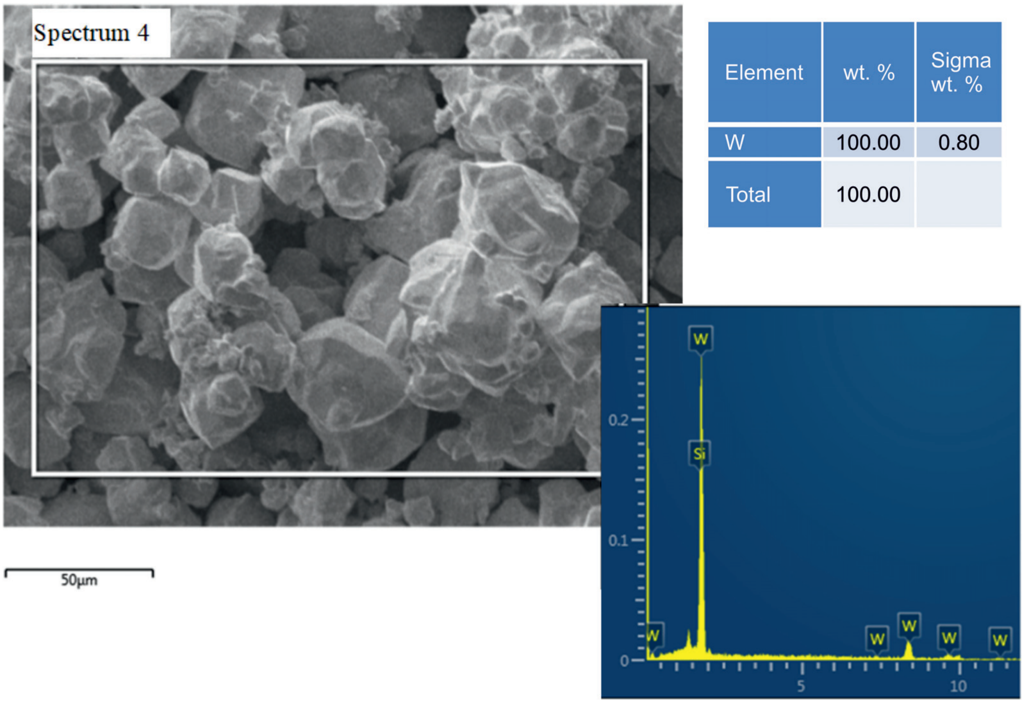


Fig. 9. Micrograph of pure tungsten metal powder obtained from pure tungsten trioxide

of 12.0–20.0 µm. The process of obtaining the hard alloy consisted of grinding a mixture of metallic tungsten and graphite powders in a mill with alcohol, evaporating the pulp, sifting, mixing with a plasticizer, pressing the teeth, drying and hydrogen sintering.

For pressing the teeth, special hard alloy punches, made of the *VK20* (80 % *W*, 20 % *Co*) alloy, were fabricated to increase the pressing pressure to achieve its high density, uniformity, strength and wear resistance.



Element	wt. %	Sigma wt. %
W	100.00	0.80
Total	100.00	

Fig. 10. Results of elemental analysis of the synthesized sample of pure tungsten metal powder

During the tooth pressing stage, a number of issues were addressed to eliminate the tendency of pressing cracks, resulting from the increased dispersion of the pressing powder [20]. Characteristic cracks were formed perpendicular to the pressing vector, due to the delamination of the pressing powder, as a result of the so-called "*spring effect*", associated with the occurrence of a pressure gradient. Fig. 11 demonstrates delamination cracks occurring during the pressing of teeth, made of highly dispersed pressing powders.

When loading the upper working surface of the ballistic tooth with the upper punch, a horizontal annular layer of compacta was found on the lateral cylindrical surface, located near the upper spherical surface. The tooth surface, formed in contact with the upper punch, was found to be characterised by the formation of a porous structure with depressions, that is, with the formation of the "*reptile skin*".

In order to prevent the occurence of delamination cracks in the area of the upper working part of the tooth, where the greatest strength and wear resistance are required, and to exclude the formation of the "*reptile skin*", the tooth shape was changed from ballistic to semi-ballistic [21, 22]. As a result of changing the shape, previously subjected to the specified press defects, the upper surface of the tooth came into contact with the lower punch. In this case, the upper punch with the modified surface shape formed the lower part of the tooth.

Fig. 11 shows the samples of stamped semi-finished products of ballistic and semi-ballistic teeth. Subsequent operational tests confirmed the correctness of changing the tooth shape to semi-ballistic.

Figs. 12 and 13 present the condition of tooth face surfaces when manufacturing in ballistic and semi-ballistic shapes.

The physical and chemical parameters of carbide tooth samples, sintered in a hydrogen furnace under various modes, were tested [23, 24]. The test results showed the compliance of the obtained tooth samples with the normative requirements for the *VK10-KC* alloy (Table 1).

Compared to *Atlas Copco* (Sweden) bits, the hardness and the grain size differ by no more than 2.5 %. The hardness of the teeth on the *Atlas Copco* tool is 88.3 HRA. This is almost identical to the hardness of the teeth, obtained by the developed technology. The average grain size is also almost the same; for *Atlas Copco* teeth it is 4.1 μm. This also does not differ significantly from the grain size of the teeth obtained using the developed technology.

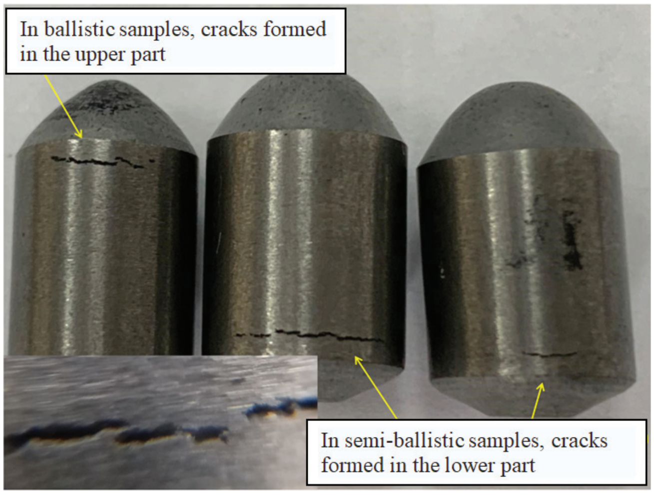
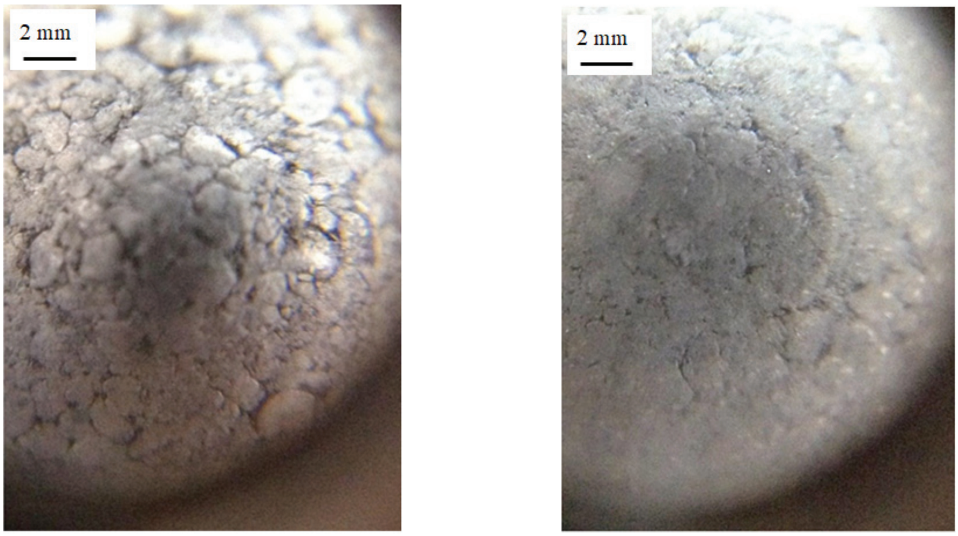
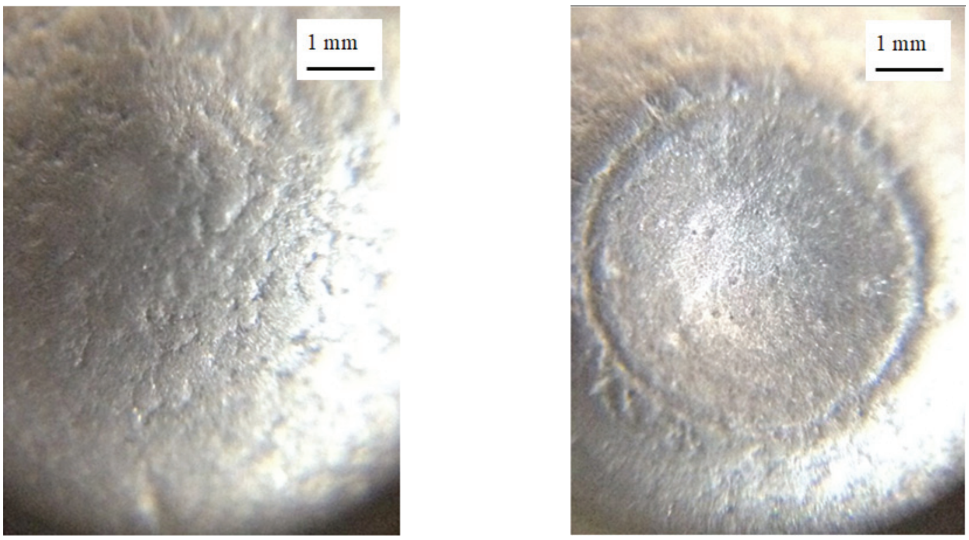


Fig. 11. Areas of localization of delamination cracks in hard alloy. Ballistic and semi-ballistic teeth



a *b*

Fig. 12. Working surfaces of teeth of ballistic (*a*) and semi-ballistic (*b*) shapes



a *b*

Fig. 13. Sample of working (*a*) and reverse (*b*) surfaces of a semi-ballistic carbide tooth

Table 1

Results of comparative tests of physical and chemical properties of carbide teeth sintered under different conditions

Analysed parameters	Properties of teeth sintered by *method 1*	Properties of teeth sintered by *method 2*	Technical requirements for the *VK10* (90 %*W*; 10 % *Co*) alloy
Density, g/cm^3	14.55	14.51	14.43–14.63
Hardness, HRA	87.8	87.8	87.4–88.2
Coercive force, E	87	80	70–90
Average grain size, µm	4.3	4.2	Not regulated
Microstructure	Equiaxial grain structure	Equiaxial grain structure	Homogeneous, without coarse grains and cobalt clusters
C_{total} , %	5.40	5.52	5.46–5.54

Comparative tests of bits manufactured using different technologies

A 3*D* model of a pin crown and a programme for its manufacture on a five-axis *CNC* machine (*SNKexl 80*) were developed for the production of steel crown bodies. The experimental crowns were made of *0.35 C-Cr-Mn-Si* steel with the subsequent hardening and grinding up to *Ra* of 1.6.

The final assembly of *KNSh 40×25* bits was performed by the cold pressing of teeth, sharpened to a tooth cone angle of 39 degrees. Experimental batches of *KNSh 40×25* bits were manufactured for production testing and underwent operational tests at several mines.

Several batches of experimental *KNSh 40×25* bits were tested at *Kyzyl-Olma* mines of the *Angren Mining Administration*, when drilling rocks with a hardness of ***f*** = 14–15, with a drilling result of 48.2 meters, as well as for rocks with ***f*** = 12–16 with a result of 46.3 meters, with wear of 10–15 %.

The bits were also tested while drilling the rocks a hardness of ***f*** =14-17 in conditions of the *Kauldy* mine with an average result of four penetrations of 49.5 meters. Fifteen *KNSh 40×25* bits were also tested at the *Chadak* mine in adits with a rock hardness of ***f*** =16–18, the drilling results ranged from 47 to 58 meters.

The certificates of industrial tests for the suitability of *KNSh 40×25* drill bits manufactured at *NPP* for work at the *Angren*, *Kauldi* and *Chadak* mines were received.

The work performed on the industrial operation of the experimental bits showed that its durability is inferior to the bits manufactured by *Atlas Copco* (Sweden) by no more than 14-17 %.

When mastering the production of hard-alloy pin bits (*KNSh 40×25*) at *Almalyk MMC JSC* enterprise, it is expected that a significant annual economic effect will be obtained due to its lower cost in comparison with *Atlas Copco* bits (Sweden).

Conclusion

Based on the results of the conducted research, the main reasons for the rapid failure of the drill bit teeth produced by *NPO AGMK* were identified. Studies showed that the main reasons for its destruction are a poor structure (coarse grains and the presence of microdefects). Also, the unsuccessful shape of the tooth surface significantly reduces the resistance. The work carried out to optimize the technology for manufacturing the teeth of the bits made it possible to significantly increase its durability. For manufacturing, a purer tungsten powder of lower dispersion was used, the shape of the tooth surface was optimized to semi-ballistic. Changes were also made to the sintering mode and subsequent agening of the teeth. As a result, an improved technology for manufacturing teeth from hard alloy *VK10-KS* was developed. The teeth manufactured using the developed technology showed comparable resistance to the teeth manufactured by European manufacturers (*Atlas Copco*, Sweden). At the same time, the cost of bits with teeth manufactured using the *NPO AGMK* technology is significantly lower.

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Conflicts of Interest

The authors declare no conflict of interest.