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About the experience of using hardmetals in the production of roller cone bits at Volgaburmash JSC

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Abstract: Since 2017, Volgaburmash JSC (Samara, Russia) tested purchased 90%WC–10%Co carbide powder mixtures and finished carbide drill bits from various manufacturers. The work was carried out in order to check the possibility of using purchased products as raw materials at the plant to reduce the production cycle for the manufacture of carbide inserts for roller cone bits. This intercommodity substitution (outsourcing) is carried out with the aim of potential cone bit cost reduction and production process acceleration so that the plant can operate in the heavily competitive environment of foreign and domestic markets. The article focuses on the analysis and detailed comparison of the micro- and macrostructure, physical, mechanical, chemical and processing properties of purchased hard-alloy mixtures and sintered inserts of various manufacturers including Volgaburmash JSC. All properties of materials under study were determined in accordance with the VBM JSC company standard STP 582-17. Much attention is paid to comparing crack resistance or Palmqvist fracture toughness values of the alloy and analysis of microstructure images and fracture propagation pattern after using scanning electron microscopy tests. In addition, consideration is given to such important hard alloy properties as hardness and transverse bending strength. Based on the results of the conducted research, conclusions are presented on the expediency of using purchased hard-alloy materials at the Volgaburmash JSC metallurgical shop in comparison with internally manufactured materials.

Keywords: roller cone bits, tungsten-cobalt granular mixtures, hard alloys, bit inserts, structure, mechanical properties, outsourcing.

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Об опыте применения твердых сплавов в производстве буровых шарошечных долот в АО «Волгабурмаш»

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Аннотация: С 2017 г. на предприятии АО «Волгабурмаш» (г. Самара, Россия) проводились мероприятия по испытанию покупных твердосплавных порошковых смесей состава 90%WC–10%Co и готовых твердосплавных зубков различных производителей. Работа велась с целью оценки возможности применения покупных изделий в качестве исходных материалов на предприятии для сокращения производственного цикла изготовления твердосплавного вооружения буровых шарошечных долот. Данные работы по товарозамещению (аутсорсингу) проводятся с целью возможного снижения себестоимости шарошечного долота и ускорения процесса его изготовления для функционирования предприятия в условиях острой рыночной конкуренции на внешнем и внутреннем рынках. Статья посвящена анализу и подробному сравнению микро- и макроструктуры, физических, механических, химических и технологических свойств покупных твердосплавных смесей и спеченных зубков различных производителей, в том числе и АО «Волгабурмаш». Определение всех характеристик исследуемых материалов проводилось в соответствии со стандартом предприятия СТП 582-17. Большое внимание уделено сравнению значений трещиностойкости сплавов, или вязкости разрушения по Палмквисту, и анализу снимков микроструктуры и характера распространения трещины после испытаний с использованием сканирующей электронной микроскопии. Также рассмотрены такие важные характеристики сплава, как твердость и предел прочности при поперечном изгибе. На основе результатов проведенных исследований представлены выводы о целесообразности использования в металлургическом цехе АО «Волгабурмаш» покупных твердых сплавов в сравнении с материалами собственного производства.

Ключевые слова: буровые шарошечные долота, вольфрамокобальтовые гранулированные смеси, твердые сплавы, зубки долот, структура, механические свойства, аутсорсинг.

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Introduction

Tungsten-cobalt (WC—Co) cemented carbides or sintered hardmetals are extensively used in industry for their high hardness, strength, cracking, and wear resistance [1—4]. The most common applications are cutting tools and dies. Heat-resistant drill bits operating in aggressive environments in the Far North and the Arctic are also made of such materials [5]. Drill rig bit failures due to the rapid wear of the hardmetal inserts are quite common. If the bit is operated within the specified limits, but its hardmetal inserts still fail prematurely, a possible reason is improper hardmetal or defects in its structure [6].

Volgaburmash (Samara) is one of the largest Russian drill bit manufacturers. The company operates a hardmetal metallurgical facility. Their global and domestic rock drilling tools markets are highly competitive. Consumers expect high tool quality and affordable prices.

One strategy aimed at reducing the cost of a roller cone bit and accelerating its manufacturing is the use of commercially available components to simplify the number of manufacturing operations [4, 7]. Sintered hardmetal manufacturing is very complex. It involves a large number (>20) of labor-intensive operations and expensive equipment [8—10].

In this study, we considered the following products and components from various manufacturers.

• Commercially available mixed cobalt/tungsten powders. Products from such powders are made by semi-automatic compression shaping and subsequent vacuum sintering. No in-house powder production is required.

• Sintered hardmetal inserts. The bits are custom-made to customer-provided shapes and dimensions. Using such raw materials significantly accelerates hardmetal product manufacturing and only machining is required. No powder making, compression shaping and vacuum sintering are necessary.

This study is a detailed investigation and comparison of the composition, microstructure, physical, mechanical properties, and manufacturability of commercially available WC—Co hardmetal powders and sintered bit inserts from various manufacturers including Volgaburmash. The applicability of the powders was assessed.

Materials

The following substances were studied.

1. Granulated tungsten-cobalt powders (Table. 1), containing 90 wt.% WC and 10 ± 0.2 wt.%: Co; WC grain size up to 3 μm; paraffin-based binder. Hardmetal powder granules are spherical. They are used for compression shaping of hardmetal drill bit components (inserts, mud gun nozzles, thrust bearings, etc.) The powders were analyzed for compliance with the STP 582-17 company standard, Volgaburmash.

2. Sintered hardmetal inserts from various manufacturers compliant with STP 582-17 (Table 2).

Table 1. **Granular carbide mixtures**

Таблица 1. Гранулированные твердосплавные смеси

Sample No.	Manufacturer
1.1	Volgaburmash, Russia
1.2	Supplier 1, Germany
1.3	Supplier 2, China
1.4	Supplier 3, Russia
1.5	Supplier 4, Russia

Table 2. **Sintered carbide inserts**

Таблица 2. Спеченные твердосплавные зубки

Sample No.	Co, wt.%	Manufacturer
2.1	6	Volgaburmash, Russia
2.2	10	
2.3	15	
2.4	6	Supplier 1, Russia
2.5	10	
2.6	13	
2.7	10 (functional gradient alloy)	Supplier 2, Germany
2.8	10	Supplier 3, China
2.9	6	Supplier 4, Sweden
2.10	10	Supplier 5, Germany

Methods

We used a Jeol JSM 6390A scanning electron microscope (SEM) (JEOL Ltd., Japan) to examine the morphology and estimate the particle sizes and grain-size distribution of the hardmetal powders.

We performed liquid-phase sintering in a vacuum at 1400 ± 30 °C, in order to produce the final structure of the hardmetal samples to be studied [11—13]. We estimated the total (C_{tot}) and free (C_{free}) carbon in the tungsten hardmetals using the gravimetric method according to GOST 25999-83 (ISO 3907:2009) [14]. (The total carbon content in WC—10%Co alloys should be 5.48—5.56 wt.%. It is not rated.)

The density was determined by the hydrostatic method (three samples selected from the batch) according to GOST 20018-74. Coercivity was measured according to ISO 3326:2013 (it decreases as the cobalt content increases, see [15]). The Rockwell hardness of the sintered hardmetal was determined according to GOST 25172-82 (ISO 3878-83) at a 600 N load [16]. The transverse rupture strength was measured according to GOST 20019-74 (ISO 3327:2009). The residual hardmetal porosity was measured using the references from GOST 9391-80 (ISO 4505-1978).

The hardmetal microstructure was investigated using the metallographic method according to ISO 4499:2020 with an Axiotech 100HD-3D optical microscope (Carl Zeiss, Germany), up to $1600^{\times}$. The samples were pre-treated with Murakami surface etching solution [17]. For all hardmetal grades, no free carbon or η-phase (double tungsten carbide and lacelike or lakelike cobalt inclusions) is allowed. The microstructure deviations were evaluated pursuant to the STP 582-17 company standard.

We paid considerable attention to studying crack resistance as the material's ability to resist crack propagation and, consequently, failure. In the case of WC—Co hardmetals used in drill bit inserts, the fracture toughness is the best metric of crack resistance. This is a structure-sensitive property. Its evaluation helps assess the sensitivity of the material's crack propagation resistance [18, 19]. We applied the Palmqvist toughness test according to ISO 28079:2009, in order to estimate the crack resistance (W_k, $MN \cdot m^{-3/2}$) of the sintered hardmetal.

A Jeol JSM 6390A scanning electron microscope [13, 19] was used for a more detailed study of the sample surface and crack propagation. Our earlier works [20, 21] present the crack resistance analysis for hardmetals and the actual crack resistance values.

The hardness, crack resistance, and microstructure of the samples were studied at 2 mm below the insert surface. It is the average hardmetal wear (for the insert business end) when the insert becomes unusable.

Results and Discussion

The SEM images (Fig. 1) we obtained show the morphology and particle sizes of the granulated hardmetal powders. It can be seen that powders *1.1* and *1.2* have a distinct spherical shape of 50—200 μm granules and are homogeneous. The powder *1.3*, *1.4*, and *1.5* granules were partially destroyed and contaminated with a finer fraction. The reason is the powder grinding through circulation in which the top layers with a higher density destroy the bottom layers. In the case of powder *1.5*, the particle size is not uniform. In order to avoid this, additional operations such as classification and drumming (to make the granules spherical) are required. This could slow down and complicate the powder manufacturing process and increase the costs as there would be some powder loss. Therefore, should Volgaburmash completely cease in-house powder production and switch to third-party supplies, the recovery of powder loss would be impossible, leading to an increase in costs.

Table 3 lists the chemical composition and some manufacturing properties of the granulated hardmetal powders. With regard to the manufacturing properties, samples *1.2*, *1.3*, and *1.4* showed apparent density and fluidity deviations. Subsequently, these led to issues with compression shaping using semi-automatic presses. The reason is the heterogeneity of the powder granules. The paraffin content in powder *1.4* exceeds the threshold. It may cause unpredictable shrinkage during sintering and affect the carbon content.

Fig. 2 shows the structures of the hardmetals sintered from granulated powders *1.1—1.5* (refer to Table 1). The microstructure of the hardmetals generally meets the requirements of the STP 582-17 company standard. However, photo *1.3* shows a segregation area 27 μm in size and two compounding spots (combined area up to 10 μm). Hardmetal *1.5* also features a cluster of crystals

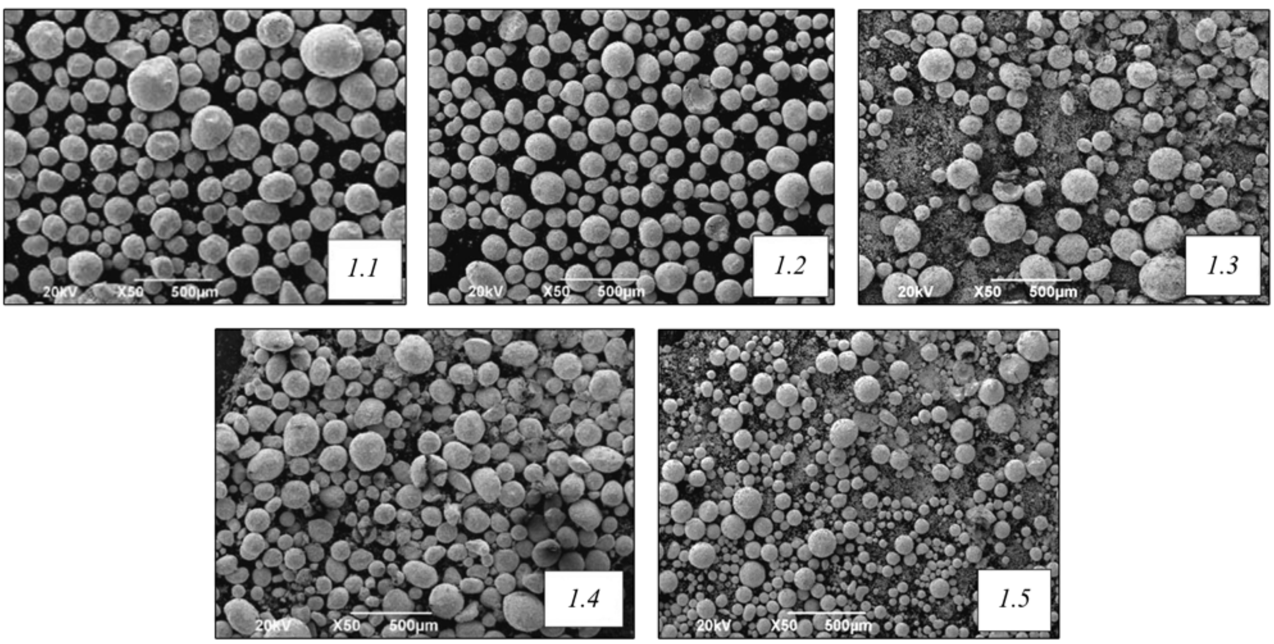

Fig. 1. Micrographs of samples of granulated carbide mixtures *1.1–1.5* (see Table 1)
×50 magnification

Рис. 1. Микрофотографии образцов гранулированных твердосплавных смесей *1.1–1.5* (см. табл. 1)
Увеличение 50$^{\times}$

175 μm in size and a 13 μm compounding area. Note that these deviations are within the tolerances specified in the Volgaburmash company standard.

Table 4 lists the physical and mechanical properties of sintered samples *1.1—1.5*: density (ρ), hardness (*HRA*), coercivity (H_c), transverse rupture strength (σ_{rs}), average grain size (davg), fracture toughness (W_k) and crack length (*l*).

Next, we compared the structure and properties of the hardmetal inserts produced by different manufacturers (refer to Table 2). Table 5 lists the values for samples containing 10 wt.% Co (refer to Table 2), while Fig. 3 shows their structures.

Sample *2.7* is produced using the manufacturer's proprietary technology. It is a functionally gradient material which indicates different Co content across the

Table 3. **Composition and properties of hard alloy mixtures studied**

Таблица 3. Состав и свойства исследуемых твердосплавных смесей

Sample No.	Content, wt.%				Apparent density, g/cm^3	Fluidity, sec.
	C_{tot}	C_{fixed}	Co	Paraffin		
Rated values	5.48–5.56	≤0.05	10 ± 0.5	2 ± 0.25	3.45 ± 3.65	≤30
1.1	5.56	0.02	9.9	2.25	3.57	28
1.2	5.56	0.03	9.9	1.92	4.07	34.5
1.3	5.59	0.04	10.3	2.06	3.22	35
1.4	5.61	0.02	10.0	2.33	3.49	32
1.5	5.68	0.04	9.9	2.03	3.59	30

Note. The values in bold deviate from the rated ranges.

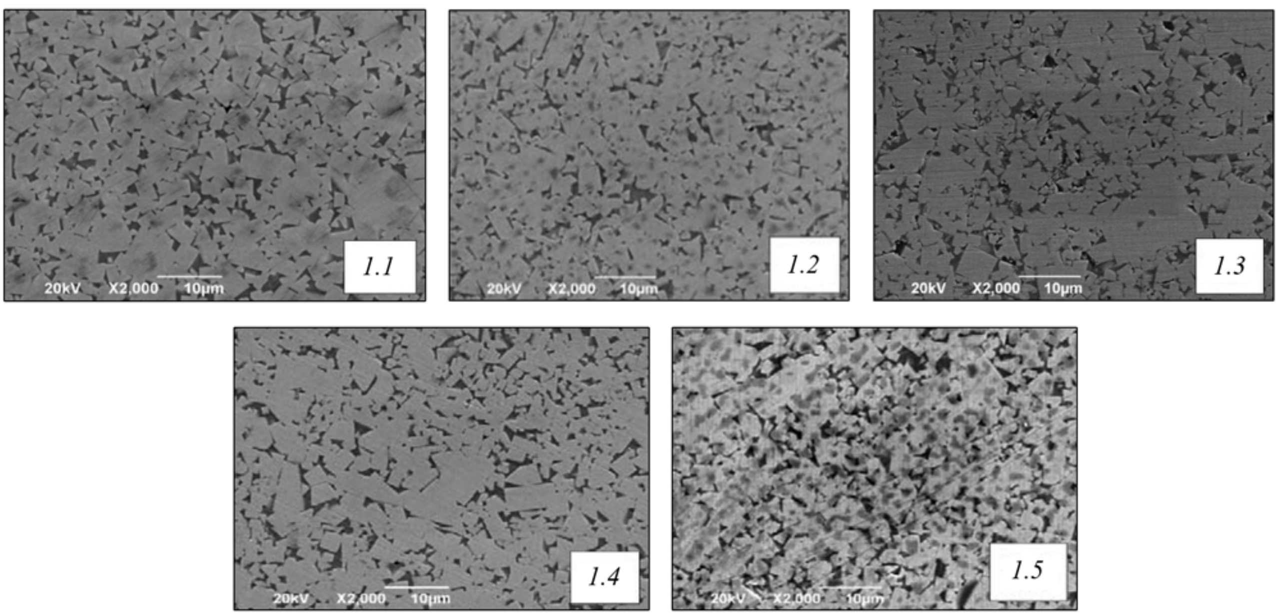

Fig. 2. Structure photographs of alloys sintered from mixtures *1.1–1.5*
×2000 magnification

Рис. 2. Фотографии структуры сплавов, спеченных из смесей *1.1–1.5*
Увеличение – 2000×

Table 4. **Physical and mechanical properties of sintered carbide samples**

Таблица 4. Физико-механические свойства спеченных твердосплавных образцов

Sample No.	ρ, g/cm^3	*HRA*	H_c, Oe	σ_{rs}, N/mm^2	d_{avg}, μm	W_k, MN·m$^{-3/2}$	*l*, μm
Rated values	14.5 ± 0.1	88.2 ± 0.3	75–95	≥2450	2.5–3.0	Actual*	Actual*
1.1	14.53	88.3	83	2960	2.6	17.6	86
1.2	14.51	88.4	87	3150	2.5	17.5	89
1.3	14.47	88.3	97	2670	2.6	15.9	107
1.4	14.51	88.3	79	2900	2.6	16.8	97
1.5	14.53	88.3	83	2960	2.6	17.3	82

* The actual value is for reference only. It is not rated.

Table 5. **Physical and mechanical properties of inserts with 10 wt.% Co content**

Таблица 5. Физические и механические свойства зубков, содержащих 10 мас.% Co

Sample No.	ρ, g/cm^3	*HRA*	H_c, Oe	σ_{rs}, N/mm^2	d_{avg}, μm	W_k, MN·m$^{-3/2}$	l, μm
Rated values	14.53 ± 0.1	88.2 ± 0.3	75–95	≥2450	2.5–3.0	Actual	Actual
2.2	14.53	88.3	83	2960	2.6	17.1	82
2.5	14.53	88.3	84	2900	2.5	17.2	81
2.7	14.55	88.8	90	2950	2.7	16.2	90
2.8	14.56	88.4	91	2910	2.4	17.0	69
2.10	14.53	88.0	87	2850	2.5	16.8	87

Note. The values in bold deviate from the required ranges.

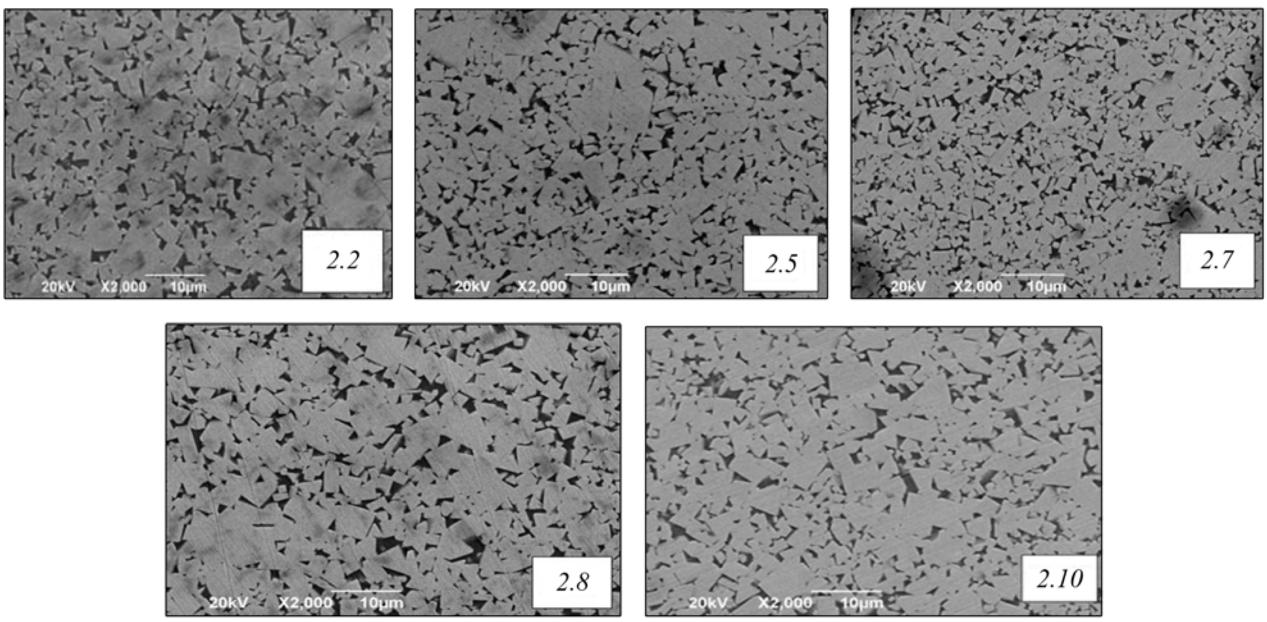

Fig. 3. Structure photographs of inserts with 10 wt.% Co content
×2000 magnification

Рис. 3. Фотографии структуры зубков, содержащих 10 мас. % Co
Увеличение 2000×

Table 6. **Physical and mechanical properties of inserts with 13 and 15 wt.% Co content**

Таблица 6. Физические и механические свойства зубков, содержащих 13 и 15 мас.% Co

Sample No.	ρ, g/cm^3	*HRA*	H_c, Oe	σ_{rs}, N/mm^2	d_{avg}, μm	W_k, MN·m$^{-3/2}$	*l*, μm
Rated values	14.0 ± 0.1	86.5 ± 0.5	70–90	≥2700	2.5–3.5	Actual	Actual
2.3	13.99	87.1	79	3130	2.4	20.3	60
2.6	14.25	86.6	75	2750	2.8	20.5	56

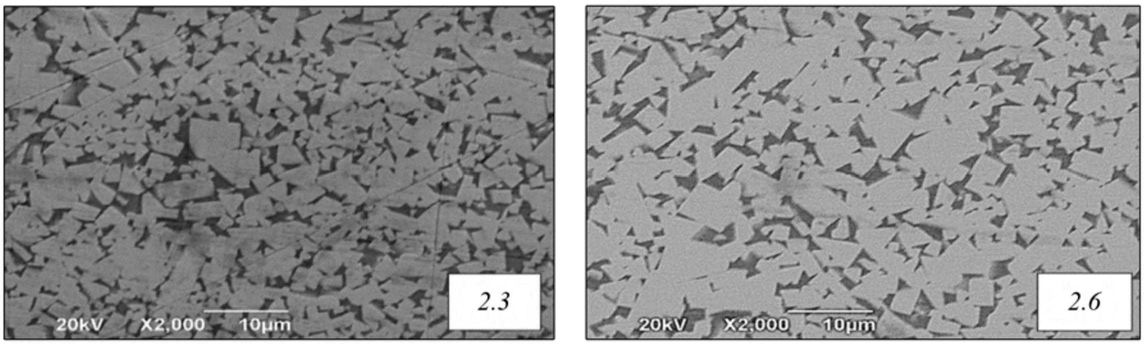

Fig. 4. Structure photographs of inserts with 15 and 13 wt.% Co content
×2000 magnification

Рис. 4. Фотографии структуры зубков, содержащих 15 и 13 мас.% Co
Увеличение 2000$^{\times}$

product. This affects the physical and mechanical properties of the insert.

The analysis showed that the structure is compliant with the company standard. Insert *2.8* has a 57 μm segregation. Samples *2.5* and *2.10* have two compounding sites 11 and 7 μm in size, respectively. Sample *2.2* has a cluster of crystals with a 124 μm total area. Note that all of the above is compliant with the STP company standard.

Table 6 lists the physical and mechanical properties of the hardmetal inserts containing 13 and 15 wt.% Co. Fig. 4 shows the photos of their microstructures. Insert *2.6* has two WC segregation defects with a total area of 51 μm, which is compliant with the company standard.

Table 7 lists the physical and mechanical properties of the hardmetal inserts containing 6 wt.% of Co. Fig. 5 shows their microstructures. Sample *2.1* features two areas of WC crystal aggregation, 103 μm total size. Insert *2.9* has one compounding area 8 μm in size, and three segregation areas 72 μm in size. Such deviations are also compliant with the company standard.

Detailed analysis of the crack showed that the samples mostly have intergranular fractures (at the WC grain boundaries). The cracks propagate along the cobalt binder [22]. Transcrystalline splits in the 10 wt.% Co hardmetal are rare. They usually occur in more ductile alloys with higher cobalt content. In the case of 13 and 15 wt.% Co hardmetals, fractures occur along the WC grains, as can be seen in Fig. 6 (sample *2.3*).

Conclusions

In this study, we compared the structure and properties of the granulated hardmetal powder (refer to Table 1) and sintered hardmetal inserts produced by various manufacturers (refer to Table 2) taking into account the costs and lead time. We arrived at the following conclusions about their possible applications for making hardmetal drill bit inserts by Volgaburmash.

1. Commercially available hardmetal powders *1.2* and *1.5* better match the requirements of the Volgaburmash STP 582-17 standard, but are more expensive, while the average delivery time is about 2 months.

Table 7. **Physical and mechanical properties of inserts with 6 wt.% Co content**

Таблица 7. Физические и механические свойства зубков, содержащих 6 мас.% Co

Sample No.	ρ, g/cm^3	*HRA*	H_c, Oe	σ_{rs}, N/mm^2	d_{avg}, μm	W_k, MN·m$^{-3/2}$	*l*, μm
Rated values	14.95 ± 0.1	90.1 ± 0.5	110–145	≥2300	2.0–2.5	Actual	Actual
2.1	14.91	90.3	132	2420	2.2	13.1	99
2.4	14.86	90.5	107	2670	2.5	13.0	96
2.9	14.98	90.4	130	2750	2.7	12.6	103

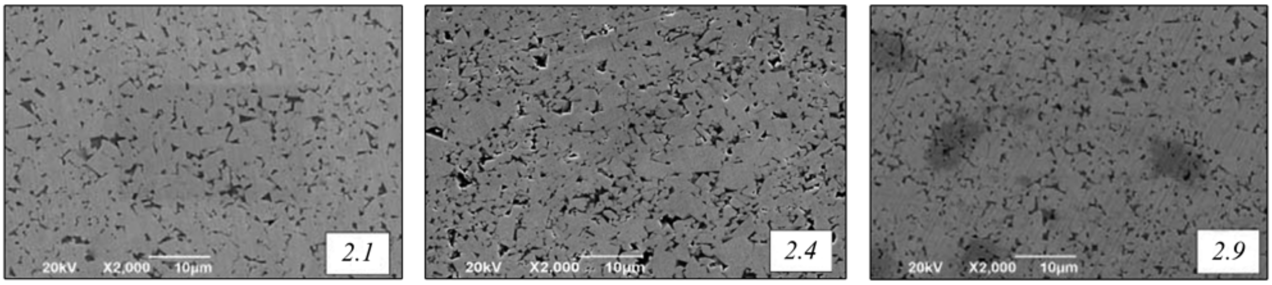

Fig. 5. Structure photographs of inserts with 6 wt.% Co content
× 2000 magnification

Рис. 5. Фотографии структуры зубков, содержащих 6 мас.% Co
Увеличение 2000$^{\times}$

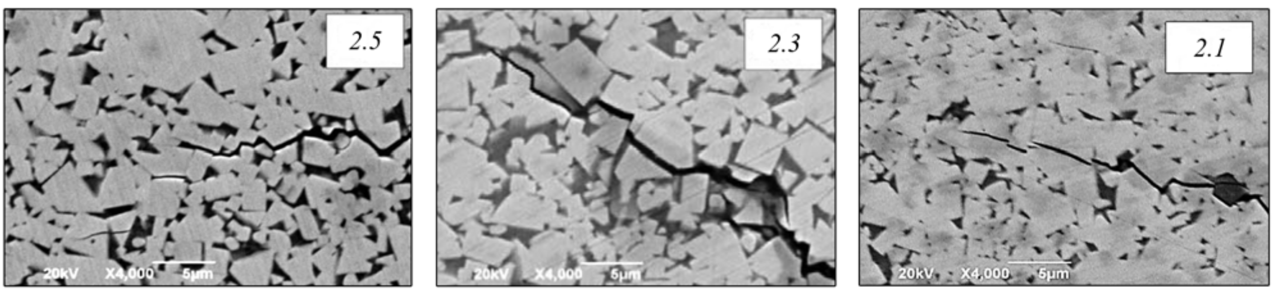

Fig. 6. Fracture propagation in inserts with 10, 15 and 6 wt.% Co content
× 4000 magnification

Рис. 6. Распространение трещины в зубках, содержащих 10, 15 и 6 мас.% Co
Увеличение 4000$^{\times}$

2. The granules of the hardmetal powders *1.3* and *1.4* are partially destroyed by circulation and contaminated with fine fractions. It requires extra effort to refine these powders. They can be used as the primary raw material for hardmetal products provided that the following conditions are met:

— powder refinement operations are introduced;

— refinement leads to powder losses up to 10 wt.%;

— refinement also produces an unusable fine powder fraction;

— the cost of products made from these powders will be higher than from the in-house powder;

— the average delivery time for these powders is 1—2 months;

— if a batch fails the incoming inspection, the entire batch will have to be reprocessed.

3. The physical and mechanical properties of all the samples meet the requirements of the Volgaburmash STP 582-17 company standard. Their characteristics are nearly identical. Still, the crack resistance of sintered sample 1.3 is lower (W_k = 15.9 MN·m$^{-3/2}$) compared to others (average W_k = 17.4 MN·m$^{-3/2}$) due to the small grain size and higher free carbon content.

4. The physical and mechanical properties of all the hardmetal inserts meet the company standard and can be used for making drill bits.

5. Insert *2.9* containing 6 wt.% Co, has a homogeneous structure and high physical and mechanical properties superior to other samples due to the manufacturing process used.

6. Among the inserts containing 10 wt.% Co, sample *2.7* is functionally gradient with the cobalt content changing from the surface to the core. The hardness of the working end examined (up to 2 mm under the surface) is 89 HRA, which exceeds the required value. This is the reason for the low crack resistance W_k = = 16.1 MN·m$^{-3/2}$. Volgaburmash does not use inserts made of this hardmetal because of their shorter service life compared to the inserts manufactured in-house.

7. Samples *2.4*, *2.5*, and *2.6* meet the requirements in terms of their physical and mechanical properties. They have a homogeneous structure without any critical defects. At present (Q1 2022), inserts produced by this manufacturer are supplied to Volgaburmash. At the customer's request, these inserts are installed on the drill bits (partially or completely).

8. Insert *2.8* has medium hardness (88.4 HRA) and crack resistance (17 MN·m$^{-3/2}$) values, and its structure is homogeneous. Since the service life of these inserts is shorter compared with that of the inserts manufactured by Volgaburmash, further purchases are not recommended.

9. Sample *2.10* meets the STP582-17 company standard in terms of physical and mechanical properties, and structure. The manufacturer supplies two types of such inserts to Volgaburmash at the customer's request.

The disadvantages of the third-party hardmetal inserts are:

— higher bit manufacturing costs;

— the average delivery time for inserts is about 2 months;

— to make a new insert type, the design documentation should be amended, and a new die should be made at extra cost;

— to avoid problems with the press-fit installation of the inserts into the drill body, the lead-in chamfer on the cylindrical part (near the bottom) should be polished to increase the chamfer height. It makes the manufacturing process more complicated;

— it is not possible to deliver more inserts quickly to the customer.

For all these reasons, in-house production of hardmetal inserts is preferable.

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