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Elastic hones for polishing tooth profiles of heat-treated spur wheels for special applications

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ABSTRACT

Introduction. The most important component of the technological process of manufacturing of gear wheels of critical products is the operation of teeth honing. Special requirements are imposed on the surface quality of special-purpose gears, where imported abrasive tools were used, the supply of which in modern economic conditions is impossible. **Purpose of work:** development of formulation, technological equipment and technology of manufacturing of elastic diamond gear hones instead of imported ones for teeth honing of gear wheels of special purpose. **Research methods.** Subject of research are samples of imported elastic gear hones and created domestic analogs. The mechanical properties, morphology and chemical composition of the abrasive (diamond) layer of the working surface of the teeth and the annular gear were determined. The content of chemical elements was controlled in separate points of the surface and by scanning over the area on a scanning electron microscope. The formulation and technology of production of annular gears were determined. **Results and Discussion.** Designs of molds for forming the abrasive layer and the hub of the gear hone are developed. The peculiarities of morphology of the material of the working layer and the annular gear of the elastic diamond gear hone are revealed. On the basis of the conducted research, domestic analogs of materials of constituent elements of the gear hone are determined. Two manufacturing technologies were considered: pressing and injection molding. Two molds were made to test the technology: a simplified model consisting of two teeth and a round mold. Several methods of manufacturing hone teeth were analyzed: manufacturing of an abrasive layer with different degree of pre-vulcanization, subsequent introduction of gear material and final vulcanization of the whole product. The mechanical properties of the materials of the working abrasive layer and the annular gear were determined. The chemical composition of the components of the hone and the boundary zone are studied. As a result of the conducted research, recommendations on the formulation of the abrasive layer and the annular gear, technology of manufacturing of the gear hone intended for final treatment of teeth of heat-treated spur wheels of special purpose are given.

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Introduction

Gear honing is an operation of final processing of tooth profiles of heat-treated cylindrical wheels made of alloyed structural steels with hardness of *HRC* 50–68 [1, 2, 3]. Gear hone (abrasive shaver) is a gear wheel, the functional rim of which is made of a composite material based on a bond and abrasive materials. The hone hub is usually made of steel or aluminum alloy. The material of the gear hone rim consists of bonding and cutting elements, i.e. abrasive powders of a certain grain size made of various abrasive materials. The use of hones helps to increase the wheel load capacity by 15–20 %, and durability by 1.5–2.5 times. The most widespread gear hones were obtained when processing hardened gear wheels of 7–9 accuracy degrees.

The structural and mechanical characteristics of the composite material of gear hones largely determine its performance [4, 5, 6]. The values of these indicators (tensile and bending strength, toughness, elastic modulus, hardness) depend on the bond material, process methods of hone manufacturing, material and granularity of grinding powders.

Abrasive gear hones are made by free casting or injection molding. Epoxy resins and acrylic plastics with various plasticizers and modifiers are used as binders of abrasive polymer compositions. In addition to hones on rigid bonds with elastic modulus of 3,000–6,000 MPa, elastic hones on polyurethane, acrylic-polyurethane and hydroxyurethane bonds are used, the elastic modulus of which is 1,100–1,200 MPa. Polyurethane *SKU-PFL* and other urethane-based copolymers give increased elasticity to the hone material [7, 8].

Based on the requirements for processing gears of 7–9 accuracy degrees, the hones are made of various abrasive materials, for example, white electrocorundum with a grain size of *F* 60–*F* 90. To ensure the necessary density and strength of the hone material, up to 20 % of grinding powders with a grain size of *F* 150–*F* 180 are additionally introduced. Such a tool reduces gear errors, primarily by redistributing its values, for example, fluctuations in the measuring center-to-center distance, profile errors, improving the quality of the side surfaces of the teeth, reducing noise in the engagement of machined wheels [3, 9].

In addition to gear hones, which have grinding powders made of classical abrasive materials as cutting elements, diamond gear hones are used for tooth honing. The diamond-bearing layer is made on metal and polymer rubber bonds [4, 10]. The diamond-free base of the hones may be metallic (based on non-ferrous alloys) and rubber (elastic hones). Diamond powders with a main-fraction grain size of 28–20 μm are used for polishing gears of 5–6 accuracy degrees [11, 12].

Diamond tools are widely used in metalworking in roughing [12], finishing and precision grinding [13–15]. Certain types of diamond tools provide roughness at the level of polishing operations [16–19].

In the manufacture of automobiles, machine tools, aviation and space engineering, special diamond and abrasive tools have become widely used in the finishing operations of high-precision gear wheels [20–22]. For example, imported elastic hones are used to polish tooth surfaces after grinding [8]. The sanctions policy of the Western countries has significantly limited the access of Russian manufacturers to imported tools, and it is impossible to obtain individual items of such tools. These tools include diamond hones for polishing special-purpose gear wheels.

The purpose of work is to develop a formulation, technological equipment and technology of manufacturing of elastic diamond gear hones instead of imported ones for teeth honing of gear wheels of special purpose.

To achieve this goal, it is necessary to address the following objectives.

1. To determine the intended materials of the abrasive layer and the geared rim based on the results of the literature review, studies of the mechanical properties, morphology and chemical composition of the analyzed hone.

2. To develop and manufacture tooling for molding laboratory specimens of the gear hone.

3. To develop a formulation and manufacturing technology for elastic gear hones for honing the teeth of special-purpose gears based on the results of laboratory studies.

Research Methodology

Specimens of imported hones and created analogues were used as objects of research. The mechanical properties, morphology and chemical composition of the diamond and abrasive layer of the gear hone and the annular gear functional surface were investigated. The morphology and chemical composition were studied using a *Versa 3DFEI* scanning double-beam electron microscope. To study the morphology of the specimens, an *Altami CM0870-T* optical microscope with a high-resolution camera was also used.

Rubber mixtures were made on model *L16M* rollers. The diameter of the rollers was 100 mm. The rotation speed and the gaps between the rolls were adjustable.

The developed compositions of domestic analogues of hones on diamond, abrasive and non-abrasive bases were molded with subsequent vulcanization on a *PHG60-212/4* hot press. The specimens were made in the form of discs with a diameter of 50 mm and a height of 6–8 mm and plates of various sizes of the same height. Eight-piece specimens for rupture tests were made from the plates using stamps on the cutting plant. The tests were performed on a *RMI-60* laboratory setup. The disc specimens were designed to determine *Shore* hardness on the *LAC-J* device.

Grinding powders of green silicon carbide *64C* and diamond synthetic powders of the *AFM* grade with a grain size of 28/20 were used as an abrasive material.

Results and Discussion

The imported specimen of elastic diamond hone consists of a diamond bearing layer (the functional part) and a diamond-free annular gear (hereinafter referred to as the annular gear). The annular gear is attached to a duralumin hub. A fragment of the hone teeth functional surface after straightening with a diamond tool and gear wheel honing is shown in figure 1.

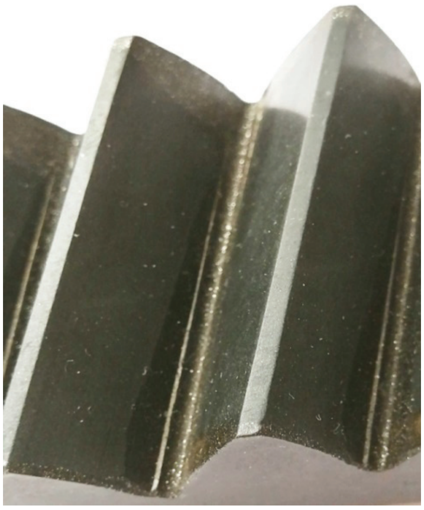


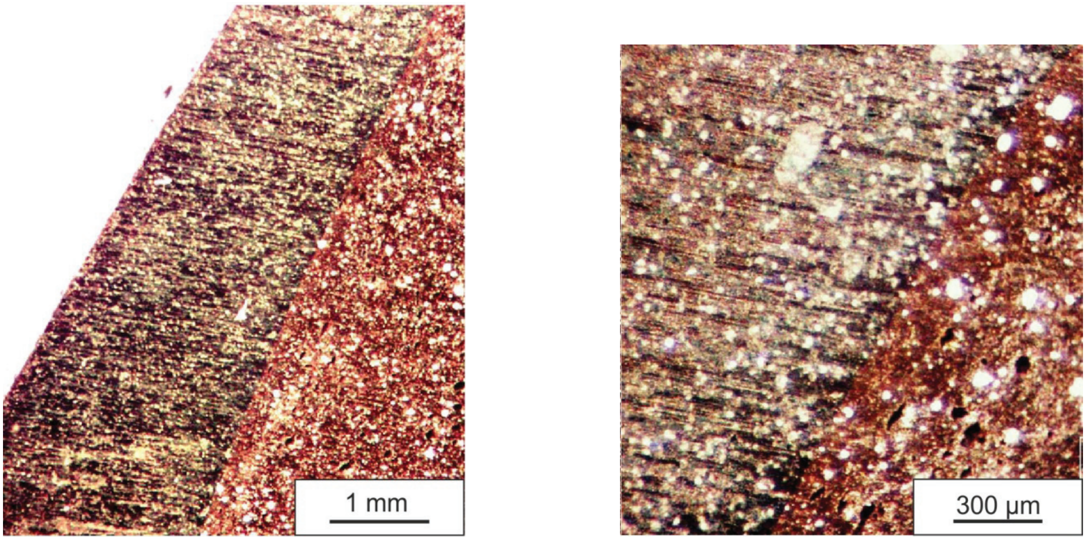
Fig. 1. Fragment of the working surface of the hone teeth

The hardness of the diamond bearing layer on the side surfaces of the hone teeth is 95–98 *Shore* units. The hardness of the annular gear material is 85–90 *Shore* units.

The morphology and chemical composition were studied on a tooth fragment of the functional part of the hone, from which cross sections with a thickness of 5 mm were cut. A diamond-bearing layer is allocated along the outer contour of the tooth (figure 2, *a*); the geared rim material lies under it. In the vast majority of the studied sections, the materials have a well-defined interface. This is evidenced by the interface condition obtained with a 50× magnification (figure 2, *b*). In the lower part of the tooth of the diamond hone under study, after its dressing, the thickness of the left diamond-bearing layer reaches 2.9 mm and decreases to 2.7–2.6 mm towards the tooth vertex (figure 2, *a*). The thickness of the right diamond bearing layer at the same tooth height is about 2.4 mm. The differences in the thicknesses of the diamond-bearing layer between the hone teeth reach 50 % on average.

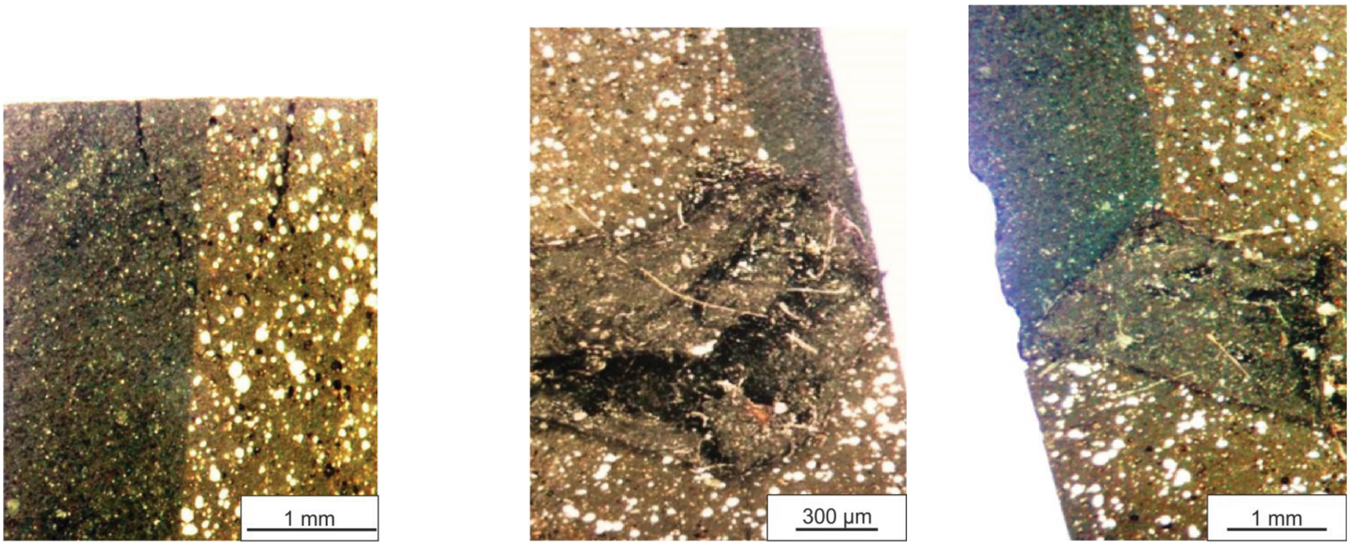
In some photographs, cracks were found in the diamond bearing layer and in the material of the annular gear (figure 3 a), diamond bearing layers of a modified structure formed at the site of transition from the tooth root to the main part of the hone (figure 3 b, c). It can be assumed that at a temperature of about 170 °C, as a result of the movement of a more mobile liquid material of the annular gear, a part of the diamond bearing layer is captured and transferred to the formed space at the level of the tooth stem. In this case, the thickness of the diamond-bearing layer may vary significantly.

In most of the analyzed tooth sections, there are no distortions of the diamond layer. A fairly clear boundary has been formed between the material of the annular gear and the diamond bearing layer at the tooth root. Delamination along the interface is rare and mainly occurs at the root of the hone tooth.



a *b*

Fig. 2. Cross section of a hone tooth at magnification of 15× (*a*) and 50× (*b*)



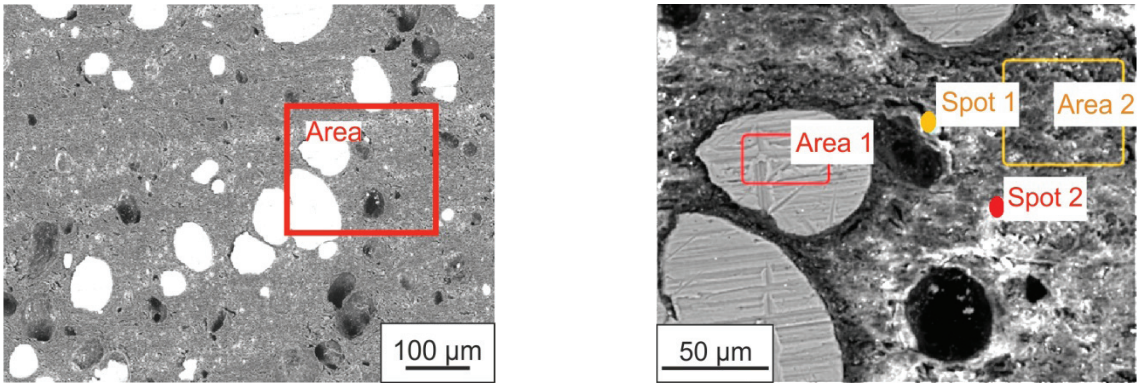
a *b* *c*

Fig. 3. Cross-section of hone teeth with surface integrity failures

The morphology and chemical composition of the hone material were studied using a scanning two-beam electron microscope. Fig. 4 a shows an electronic photograph of the annular gear cross section. Large white spots and smaller dark fragments, which are voids (craters), stand out on the surface. The craters were formed as a result of removal of aluminum powder when the test plate was cut off from the main material of the gear hone. The chemical composition was studied in the ***Area*** highlighted by a rectangle. This ***Area*** is shown in figure 4, *b*.

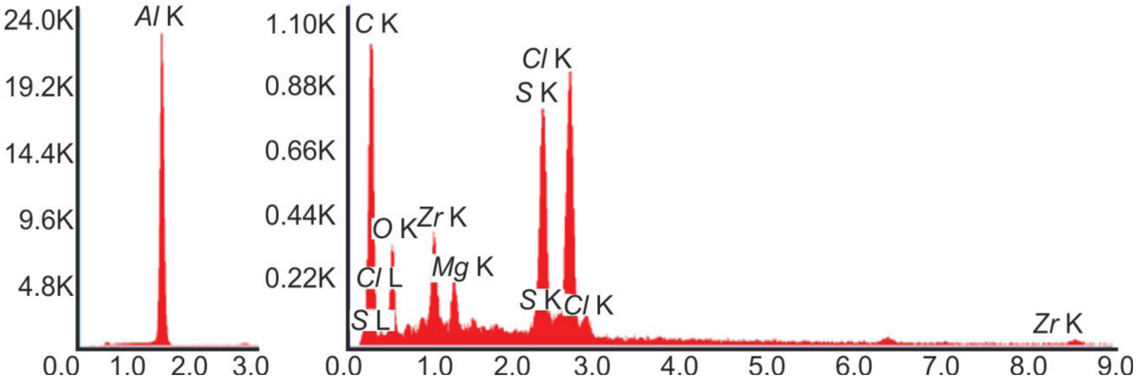
The chemical composition of the annular gear of hone was determined by scanning the surface area of gray material inclusions (***Area* 1**) and a surface area without visible inclusions (***Area* 2**). Spot analysis was performed in the area of ***Spot* 1** and ***Spot* 2**. Regardless of the size of the analyzed surface area, the diameter of the electronic probe was 50 nm. When scanning the surface, the number of measurements (spots) in the selected areas was assumed to be 400.

The main chemical element in the X-ray images at ***Spot* 1**, ***Spot* 2** and ***Area* 1** is *Al*. As an example, figure 5, *a* shows an X-ray image obtained by scanning the surface of ***Area* 1**. Similar X-ray patterns were obtained at ***Spot 1*** and ***Spot 2***. The composition of the annular gear material was determined on the surface



a *b*

Fig. 4. Annular gear cross section (*a*) and a fragment of the “Area” of this cross section (*b*)



a *b*

Fig. 5. X-ray diffraction patterns of the objects in *figure 4, b*:
a – ***Spot 1***; *b* – ***Area 2***

of ***Area 2*** (see figure 4, *b*). The selected surface area is about 2,600 μm^2. An X-ray pattern of the surface is shown in figure 5, *b*.

The main chemical element of the analyzed objects is carbon, making almost 57 % (Table). This is followed by chlorine (17 %), sulfur (12 %), oxygen (8 %), zinc (5 %) and magnesium (about 1.6 %). The chemical composition of this material is more consistent with chloroprene rubber. Nitrile butadiene rubber is also close to this chemical composition.

There are no fundamental differences between the compositions of the diamond bearing layer and the geared rim material. The composition of the diamond bearing layer contains an average of 1.5–2.0 % more sulfur, which is consistent with its higher hardness compared to the hardness of the annular gear material.

It can be assumed that the basis of the diamond bearing layer and the annular gear are two materials similar in chemical composition, for example, chloroprene and butadiene-nitrile rubbers, with the addition of various fillers (binders, softeners, stabilizers, accelerators, vulcanizers, etc.). This rubber with fillers acts as a bond for the diamond bearing layer and the annular gear material. In the first case, the bond binds and holds diamond or abrasive grains (powders), in the second it binds aluminum powder (*GOST 6058-2022*). The aluminum powder in the composition of the annular gear material performs a control function and determines the service life of the diamond hone. The appearance of light spots of aluminum powder inclusions on the dark functional surface of the hone teeth indicates the wear of the diamond bearing layer and the need to replace the abrasive tool.

Based on studies of hardness and tensile strength, the optimal range of components of the abrasive layer and annular gear material was determined. *Shore* hardness of the specimens with an abrasive is 93–95 units, with aluminum powder it is 85–88 units, ultimate strength is 14 MPa and 11 MPa, respectively.

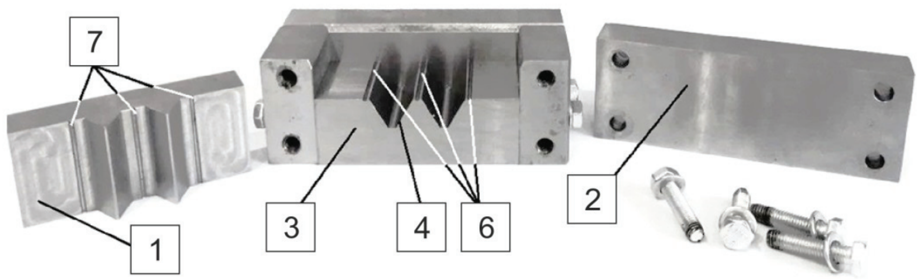
Chemical composition of the objects (see figure 4, *b*)

Object	*Element*	*Weight, %*	*Atomic, %*	*Error,%*
Spot 1	*O* K	3.1	5.1	9.4
	Al K	96.9	94.9	1.5
Spot 2	*Al* K	100.0	100.0	1.6
Area 1	*Al* K	100.0	100.0	1.6
Area 2	*C* K	56.8	75.8	10.6
	O K	8.4	8.4	12.7
	Zn L	5.2	1.3	8.5
	Mg K	1.6	1.1	9.6
	S K	11.6	5.8	3.2
	Cl K	16.7	7.6	3.2

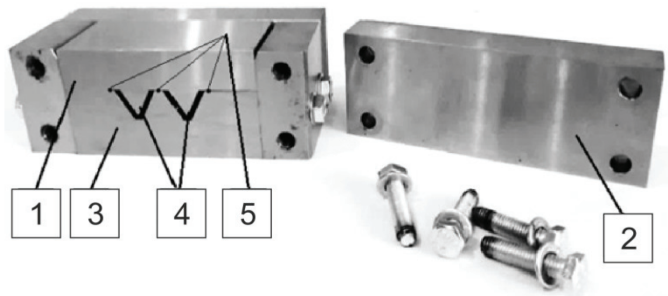
A special mold consisting of two teeth has been developed and manufactured to implement various process schemes for the hone manufacturing. Before forming the abrasive layer (figure 6, *a*), the upper plate **1** was removed from the mold. The mold had the form shown in figure 6, *b* (in the center). The side plate **2** was attached to the mold with screws (see figure 6, *a*). The prepared plates of the abrasive layer material containing the abrasive powder were placed in grooves **4** of the lower plate **3** and distributed evenly on the *V*-shaped surface of each tooth. The plates were pressed by the upper plate **1** and placed on the table of the press for forming an abrasive layer with a thickness of 3 mm, specified by the design dimensions of the mold. The excess of the molded material enters three derivation canals **5** (see figure 6, *b*). The channels are formed as a result of combining three grooves **6** on the lower plate **3** (see figure 6, *a*) with three of the same slots **7** on the upper plate **1**.

The same mold, with some modifications, is used to make a two-teeth hone model (figure 6, *b*). The preparation for molding consisted in removing the upper forming plate **1**. Then, the annular gear material was placed in the mold on the molded abrasive layer and a two-teeth hone fragment was obtained by pressing to study the mechanical, physical and chemical properties of the tool materials.

In order to exclude the established fact of displacement of the abrasive layer during molding (see figure 3), the preliminary vulcanization of the functional layer was carried out. Then, as mentioned above,



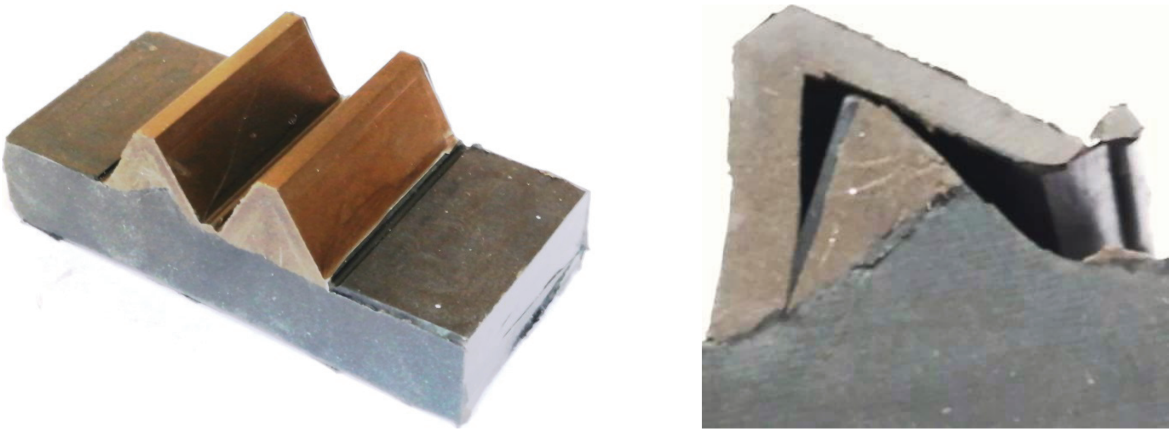
a



b

Fig. 6. A mold for forming a diamond-bearing layer (*a*) and hone teeth (*b*)

the required amount of annular gear material was placed in the mold, pressing was performed with final vulcanization. The general view of the two-teeth hone element is shown in figure 7, *a*. When trying to cut off a tooth fragment (end part) with a diamond cutting wheel, the abrasive layer separated from the annular gear material (figure 7, *b*).



a *b*

Fig. 7. Two-tooth fragment of a hone after vulcanization (*a*) and a view of the end part of a hone tooth with prevulcanized abrasive layer (*b*)

The duration of partial vulcanization was reduced by 1.5 and 2.0 times to increase the adhesion strength. The adhesion strength increased, however, with the application of force, and the abrasive layer separated. In this regard, further studies were carried out without preliminary vulcanization of the functional layer. In the left part of the photograph (figure 8) there is a functional layer containing grinding powder of green silicon carbide *63C* with a grain size of 28/20, with the annular gear material with the addition of aluminum powder in the right part. The interface of the two-layer specimen is homogeneous, without integrity violations, which ensures the necessary strength of adhesion.

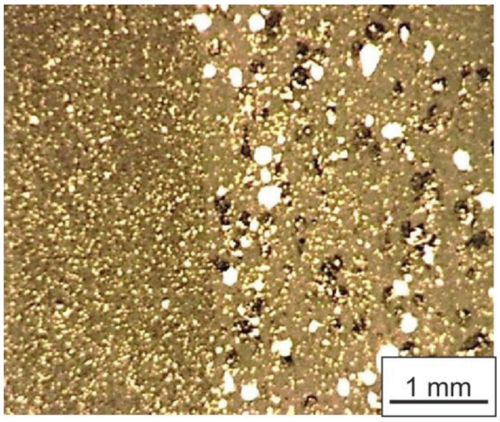
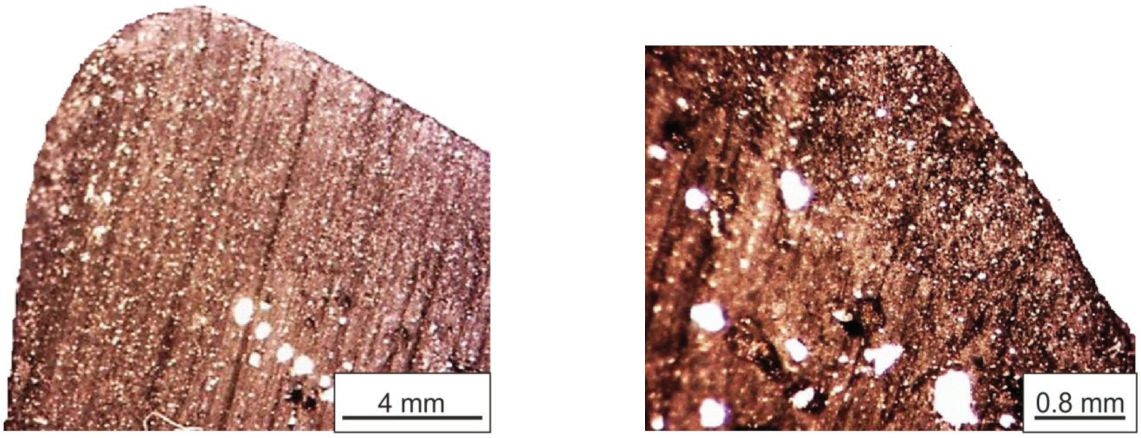


Fig. 8. Interface between the abrasive layer and the annular gear material

An experimental mold for the manufacture of a hone model with a 6 mm module, with a number of teeth of 14, was designed and manufactured. The necessary equipment for obtaining gear hone by hot injection molding was selected and manufactured. For preliminary studies, instead of diamond powder, green silicon carbide of the same grain size was used. As a result of the introduction of an additional amount of vulcanizing agents, the following *Shore* hardness values were obtained: the abrasive layer was 95 units, the annular gear material was about 90 units. The hone model was successfully tested during trial honing of a gear wheel with a diameter of 114 mm and a height of 32 mm.

Honing of gear wheels in production conditions is carried out using kerosene-oil cooling lubricants. In this regard, the influence of this cooling lubricant on the hone material was investigated. It was found that after 7 days of exposure of hone in a kerosene-oil medium, the hardness of the functional surface of the abrasive layer and the annular gear material did not change.

The hone was cut perpendicular to the axis to analyze the condition of the interface between the abrasive layer and the annular gear material. The morphology of the cross-sectional surface of the hone tooth was studied using optical and electron microscopes. The interface of the section (figure 9, *a*) is visually detected. There is a decrease in the thickness of the abrasive layer from the top of the hone tooth to its stem.

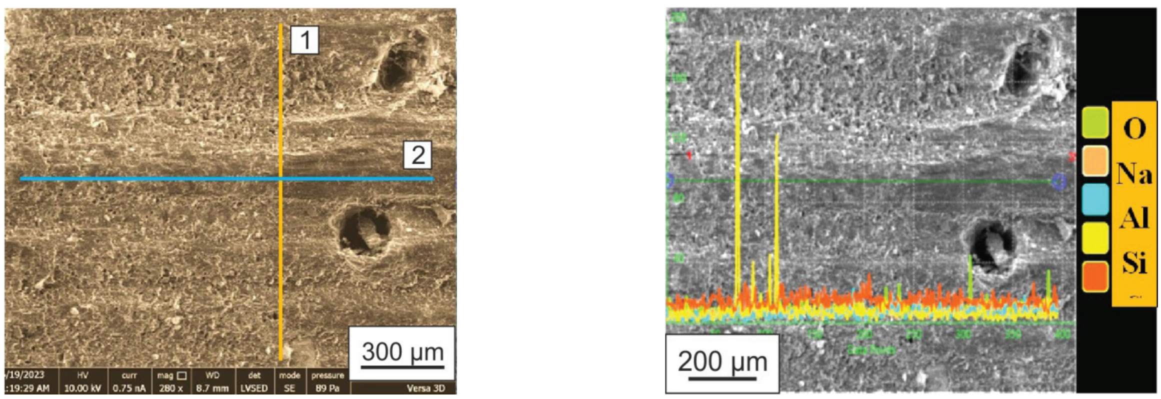


a *b*

Fig. 9. Cross sections of a hone tooth using green silicon carbide powder as an abrasive material:
a – magnification 5×; *b* – magnification 20×

A fragment of the interface between the abrasive layer and the annular gear material is presented separately at 20× magnification (figure 9, *b*). The color background allows drawing a conditional interface between the layers. The base of the material in both components is the same, which ensures strong adhesion between the abrasive layer and the material of the hone annular gear. Aluminum powder was added to the annular gear material to control the abrasive layer wear.

The chemical composition near the interface was studied using a scanning electron microscope. In figure 10, *a*, the interface between the abrasive layer and the annular gear material is indicated by vertical line **1**. The chemical composition of the treated surface was determined by horizontal line **2** passing from left to right from the area of the abrasive layer into the annular gear material. The main chemical element of the hone material is carbon, which presents in the composition of the abrasive layer and the annular gear. In this regard, carbon registration in the analysis of chemical composition was disabled.



a *b*

Fig. 10. Morphology and chemical composition at the interface between the abrasive layer
and the gear material

The chemical elements determined by X-ray spectral microanalysis in this case are oxygen *O*, sodium *Na*, aluminum *Al*, silicon *Si* and sulfur *S* (figure 10, *b*).

The content of *O, Na* and *S* in the analyzed areas of the hone is the same. In the left part, i.e., in the abrasive layer, there are individual spikes in silicon concentration, which indicates the presence of crystals of an abrasive material (silicon carbide). Due to the fact that the scanning route was laid excluding contact with aluminum powder, aluminum was not detected in the section of the interface under consideration.

The results of the X-ray spectral analysis are consistent with the previously obtained data and indicate a uniform distribution of chemical elements in the material of various parts of the hone, except for aluminum and silicon. The increased aluminum content is due to the presence of aluminum powder in the annular gear material, the increased silicon content in the abrasive layer material is due to the presence of silicon carbide crystals.

Conclusion

1. Based on the results of a literature review and the results of a study of the chemical composition of fragments of imported hone, it was found that chloroprene and butadiene-nitrile rubbers, the composition of which is close to the imported analog, may be used as a hone material.

2. Studies of the mechanical properties of laboratory specimens showed that these materials, with the addition of various fillers (humidifiers, binders, stabilizers, softeners, vulcanizing agents, accelerators, etc.), provide the necessary *Shore* hardness; for an abrasive layer, this value is 93–95 units, for a annular gear of hone it is 85–88 units, tensile strength is 14 MPa and 11 MPa, respectively.

3. To refine the formulation and production technology of the imported hone domestic analogue, a two-teeth laboratory mold was made, which allows performing the following operations: molding and heat treatment of the abrasive layer, joint molding and heat treatment of the abrasive layer and the annular gear.

4. It is established that the preliminary vulcanization of the abrasive layer has a significant effect on the strength of its adhesion to the annular gear material: with an increase in the degree of vulcanization, the adhesion force decreases. In this regard, the joint vulcanization of the abrasive layer and the annular gear is adopted in the technological process.

5. The required thickness of the abrasive layer is obtained by rolling followed by profiling in a mold without vulcanization. Further technology is implemented by injection molding and pressing methods followed by vulcanization.

6. An experimental mold for the manufacture of a hone model with a 6 mm module, with a number of teeth of 14, is designed and manufactured. The following *Shore* hardness values were obtained: the abrasive layer was 95 units, the annular gear material was about 90 units. The hone model was successfully tested during trial honing of a gear wheel.

7. After seven days of exposure in a kerosene-oil medium used in production conditions for honing operations, the hardness of the abrasive layer of the geared hone and the annular gear material did not change.

8. The developed formulation of elastic gear hone and its manufacturing technologies are accepted for testing under production conditions.

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Conflicts of Interest

The authors declare no conflict of interest.