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Improving the efficiency of metal-bonded diamond abrasive end tools by improving manufacturing technology

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ABSTRACT

Introduction. Difficult-to-machine materials with enhanced physical and mechanical properties are increasingly being used in various industries. Such materials are used in mechanical engineering for the manufacture of parts and assemblies of machines and mechanisms, in the production and processing of food products where increased operational requirements are required. In modern production, along with traditional methods of intensifying technological operations, combined and hybrid processing technologies are used. For the finishing of products, abrasive grinding with a diamond tool is used. One of the problems hindering the wide practical application of this method in industry is the fact that it has a high prime cost caused by the cost of materials used in the manufacture and the laboriousness of the tool shaping process. This leads to the need to develop a new technology for manufacturing diamond tools**. The purpose of the work** is to increase the efficiency of the end diamond abrasive tool with a metal bond by using carbon steels as a body material, increasing the strength of the connection between the body and the diamond-bearing part, as well as choosing an effective tool manufacturing technology**. Research methodology.** To gain this task, a technology for manufacturing end diamond abrasive tools is developed and tested. Allowing using the technology of capacitor welding to connect the diamond-bearing part with the shank and use medium-carbon hardened high-quality steels with a hardness of 45-60 HRC as the shank material. The strength of the connection of the body with the working diamond-bearing part of the grinding head samples is determined by tensile testing on a 1958U10 tensile machine with maximum load 100 kN. The quality of the joint is assessed visually by the presence of discontinuities in the joint, as well as by examining the microstructure and measuring the microhardness of the weld and heat-affected zones. The microhardness of the welded joint is measured using an HMV-G21ST semi-automatic microhardness tester (Shimadzu, Japan) at a load of 50 g. **Results and discussion.** Thus, the results of comparative studies allow us to assert that the strength of the connection between the shank and the working diamond-bearing part according to the proposed technology surpasses similar characteristics of the strength of the connection between the shank and the diamond-bearing layer of grinding heads obtained by the method selected by the prototype. **Conclusions**. The proposed technology for the manufacture of diamond heads increases the strength of the connection between the body and the diamond-bearing working part, reduces the cost of manufacturing the grinding heads due to the use of hardened medium-carbon steels as the material of the tool body instead of high-speed steel grades, the technology is simplified and the possibility of automating the manufacture of tools appears**.**

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Introduction

In the context of a modern economy, one of the fundamental indicators is the competitive advantage of products. In mechanical engineering, products that guarantee advanced performance characteristics of work-pieces, along with high quality characteristics, have often greater competitive advantage. Parts made

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of high-tension, hard-to-machine and nanostructured materials fully meet these criteria [1–5]. High quality indicators of such products are formed, as a rule, at finishing operations of shaping, among which abrasive processing is emphasized [6–13]. However, due to high physical and mechanical properties of the listed structural materials, not all abrasive materials deal with this task [14, 15]. Positive results are generally observed when using high-strength abrasive materials (such as diamond or cubic boron nitride). In addition, the performance of such a tool directly depends on the abrasive tool bonding [16]. Organic bonds, which are often used for machining high-strength materials, provide good cutting ability of the tool, but at the same time increase the consumption of expensive high-strength abrasives [17]. Wheels on metal bonds have a significantly lower consumption when processing high-strength materials, but, at the same time, they are more prone to loss of cutting ability as a result of the "glazing" phenomenon [15, 18, 19]. Diamond wheels on metal bonds are most effective when implementing combined processing methods [14, 19–26]. In this case, both the diamond-bearing layer and the tool body must meet the requirements of current conductivity, thermal conductivity, and strength. This is especially relevant when using diamond end tools (grinding heads) as a tool. The operational characteristics of diamond grinding heads on metal bonds, in addition to the physical and mechanical properties of the diamond layer, are also determined by the case (shank) strength properties.

The choice of diamond tools case material also depends on the bonding material [16] and the way the diamond element is attached to the tool shank. For example, diamond tools with organic bonds are made by press-fitting a diamond layer onto a case or by simultaneously pressing and sintering (polymerizing) a diamond powder blend and a case in dies. In this case, the polymerization temperature doesn't exceed 200 °C, and carbon tool steel with a hardness of up to 63 HRC can be used as the material for the diamond grinding heads case on organic bonds, in accordance with the recommendations of GOST 17122–85.

The common alloys based on Cu-Sn and Cu-Al-Zn [16] are used as materials for metal bonds of diamond tools for processing products made of high-strength materials. The temperature of diamond elements sintering on such metal bonds is 600…700 °C. When using matrix-filled materials based on copper as a bond, the temperature of diamond part sintering can reach up to 750°C [5]. Such sintering temperatures require, accordingly, the use of heat-resistant steel for the cases (shanks) of grinding heads manufacture when using standard technology, when the tool case is connected to the diamond part in the process of cold pressing, sintering and subsequent hot pressing in a heat-resistant metal mold. Therefore, in order to maintain high hardness and bending strength of the tool case during sintering and hot pressing, tool cases are recommended to be made, in accordance with GOST 17122-85, from high-speed tool steel (GOST 19265–73). Such steels are capable of maintaining high hardness and strength when heated up to 650°C, and the bending strength of high-speed steel σ_{bend} reaches 3000 MPa. Carbon tool steel, for example U8, has an ultimate bending strength of up to 2000 MPa. Steel 45 when quenched and low tempered (48 HRC) has an ultimate bending strength of 1200 MPa [27].

The required bending strength of the grinding head case material, which ensures safe and reliable working conditions for the diamond tool, is determined by the pressing force *P* during grinding. In accordance with the recommendations of GOST 17122–85, when grinding by cylindrical diamond heads of the AW type, the pressing force is 0.4 N per 1 mm of the contact-forming head, which, with a diamond part of heads maximum height of 20 mm, is 8 H. Such a pressing force leads a maximum bending stress equal to 15 MPa in a shank with a diameter of 6 mm and a range of 40 mm in the dangerous case section, which is many times lower, for example, the permissible stress $[\sigma_{bend}]$ = 270 MPa for steel 45 after quenching and low tempering, with a hardness of 48 HRC.

However, the use of non-heat-resistant tool steel or carbon structural steel as the case of metal-bonded diamond grinding heads requires additional heat treatment, quenching and low tempering of the finished tool made using a standard technology. Such a final operation in the technology of diamond grinding head manufacture is not always acceptable, due to the possibility of softening the diamond layer metal bond.

The most promising method of bonding a quenched steel case in the form of a cylindrical shank with a grinding head diamond part, as shown by preliminary studies [28, 29], is the method of butt condenser welding, carried out with arc ignition and melting of the connected surface [27]. This method is widely used in the industry for welding low-carbon steel studs with a diameter of 2 to 12 mm to thin-walled ones to case-shaped parts [16]. The use of an additional nozzle [28] to a standard condenser welding machine gun provides a butt welded joint of the tool cylindrical case (shank) with a diamond part with the required accuracy. In order to increase the joint efficiency between the case and the diamond part, the authors [29] propose an intermediate case made of steel St.3, inserted into the diamond part during its manufacture. The authors managed to show that the use of the condenser welding method, due to the high energy density and pulse shortness, does not lead to softening of the main case made of heat-strengthened tool steel U8. However, as practice shows, the use of quenched U8 carbon tool steel as a case does not always ensure the stability of joint efficiency properties between the shank and the diamond part, obtained by the condenser welding method. It is generally known [27] that the welding properties of steel deteriorate with increase in carbon content. This is usually associated with the appearance of brittle structural components in the form of martensite and residual stresses in the welded joint. Therefore, it is of practical interest to study the possibility of using intermediate-carbon structural steel as the case of diamond grinding heads, which, after quenching and low tempering, as was shown above, have a sufficient ultimate bending strength.

The work objective is to increase the efficiency of the end diamond abrasive tool on a metal bond by using carbon steels as the case material, to increase the joint efficiency between the case and the diamond-bearing part, as well to simplify the manufacturing technology of the tool.

Research methodology

The proposed way to increase the efficiency of a diamond end tool manufacture, as already noted above, is the use of the butt condenser welding with arc ignition and melting of the connected surfaces to connect the case made of quenched carbon steel with the diamond-bearing working part [27]. The condenser welding method advantages are: minimum heat-affected zone due to high energy density and pulse shortness (1...3 ms); joint efficiency; high performance and technology simplicity, and the possibility of automation [30]. In this case, the surface layer to be melted does not exceed 0.2 mm [27]. Accordingly the quenched steel shank in the process of welding to the working diamond tool layer will not lose its strength characteristics in practice, especially in the area of maximum bending stresses impact during the tool operation.

The process of condenser welding of a cylindrical case to the diamond part of the tool is recommended to be carried out with a pulsed arc using guns equipped with a spring mechanism for pressing the surfaces to be welded. Commercially available welding machines, for example, provide a bonding of such studs with a diameter from 2 to 12 mm. A mandatory requirement is the presence at the base of one of the welded elements of an axial contact tab in the form of a cylinder with a diameter of 0.6 to 0.75 mm and a height of 0.55 to 0.75 mm [31]. This is provided for two main purposes:

– allows to determine the exact place of welding of the element on the surface of the case by applying a preliminary center marking;

– provides ignition of the welding arc and steady-state combustion over the entire surface of the element at implementation of the discharge of the capacitor.

To ensure a high joint efficiency between the diamond grinding head case and the working part, in this work, a transitional steel insert 3 (Fig.1) is used in the form of a screw stud with a contact end of the RT type (GOST R 55738-2013 (ISO 13918:2008) and a height of no more than 2/3 of the head working part height. When manufacturing the working diamond part, such a stud is installed in the mold along its axis and fixed in this position with its contact end in the lower punch end hole of the press tool for cold pressing. Then the ready-made diamond powder blend is filled in a mold, and the blend is subjected to cold pressing at a pressure of 300...400 MPa. A finished diamond briquette with an insert in the form of a screw stud is removed from the mold and sintered in a vacuum or in a shielding atmosphere at a temperature of 700°C. The process of manufacturing a diamond-bearing working layer with an insert is completed by hot pressing (compaction) in a heat-resistant molding tool at a pressure of no more than 300 MPa and a temperature of no more than 500°C. Then, the finished tool is ejected from the mold. For the convenience of implement-

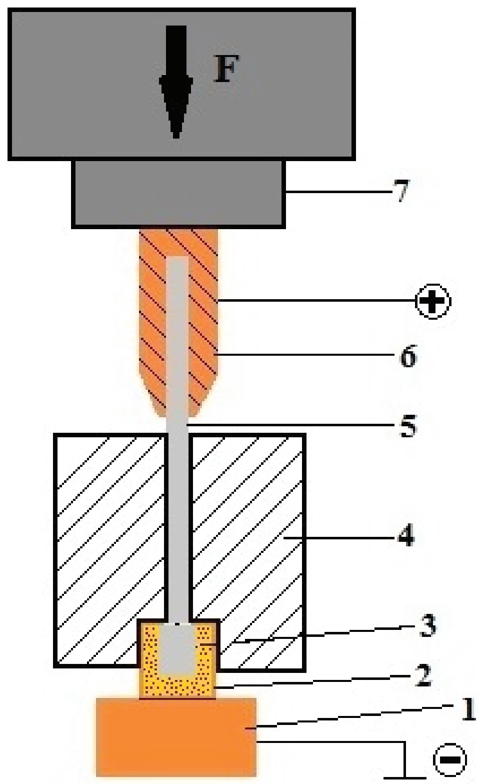

Fig. 1. Scheme of capacitor welding of a steel shank to the working part:

1 – lower copper electrode; 2 – working diamond-bearing part; 3 – steel insert in the form of a screw pin with a contact ledge; 4 – dielectric coupling; 5 – cylindrical body (shank); 6 – collet grip of the welding gun; 7 – welding gun

ing the hot additional pressing process, a cold-pressed briquette is made 0.5...1.0 mm less in diameter than the diameter of the diamond head finished working part.

Welding of the grinding head body made of quenched steel to the working diamond-bearing part of the tool by the method of condenser butt welding includes the following operations. The surfaces to be welded are pre-cleaned and degreased. Turn on the welding machine. Insert the quenched shank (5) as shown in Fig. 1 into the welding gun collet (6). The diamond head working part (2) is installed into the coupling (4) from below, with a steel insert (3) and with a contact protrusion upwards. The coupling with the diamond head inserted working part are thrust against the copper plate-electrode (1). The electrode surface shape is determined by the head working part shape. A welding gun (7) with a fixed shank is inserted into the coupling so that the shank end touches the working head contact protrusion, then press on the gun handle until the spring stops compressing. In the last turn, the discharge button on the welding gun is pressed.

For the manufacture of experimental samples of diamond grinding heads of the AW type by the method described above, for example, with a diameter of 12 mm and a height of 12 mm (GOST 17122), cylindrical cases (shanks) with a diameter of 6 mm and a length of 68 mm from different grades of quenched carbon steels 35, 45, 60 and U8 were used. The shanks made of steel, 35 and 45 were quenched to the maximum hardness in water, and those made of steel 60 and U8 were quenched in oil.

The working diamond part of all heads was made on a metal bond M2-01 with a 100 % concentration of AC32 160/125 diamond powder (GOST 9206-80) according to the above-described manufacturing technology. As an intermediate case (3), located in the center of the diamond working part, ready-made copper-plated screw studs M6 with a contact end of the PT type (GOST R 55738-2013 (ISO 13918: 2008) and 8 mm in length were used. Such steel studs of 4.8 strength class (GOST ISO 898-1-2014) have a tensile strength of at least 400 MPa and conventional yield strength of at least 320 MPa. The chemical composition is similar to that of St.3 or St.4 steels.

Condenser welding of cases made of quenched carbon steel with a diameter of 6 mm to the end of the working diamond part intermediate case was carried out on a welding machine for condenser welding of STC-2500 model in the sequence described above. The charging voltage for condensers recommended by the manufacturer for welding steel studs with a diameter of 6 mm to a steel case is 100...120 V. The samples of diamond heads under study, shown in Fig. 2, were connected to a quenched steel case according to the above technology at a condenser charging voltage of 110 V.

Subsequently, for stress relief in the welded joint, the diamond grinding heads under study, connected to the shank using the condenser welding method, were tempered at a temperature of 240 ± 10 °C for 1.5 h.

The joint quality was assessed visually by the presence of discontinuities in the joint, as well as by examining the microstructure and measuring microhardness of the weld and the heat-affected zones. The welded joint microhardness was measured using a HMV-G21ST semi-automatic microhardness tester (Shimadzu, Japan) under load of 50 g.

The joint efficiency of the case with the working diamond-bearing part of the grinding head samples was determined by the tensile test method on a breaking machine 1958U10 with a maximum load of 100 kN.

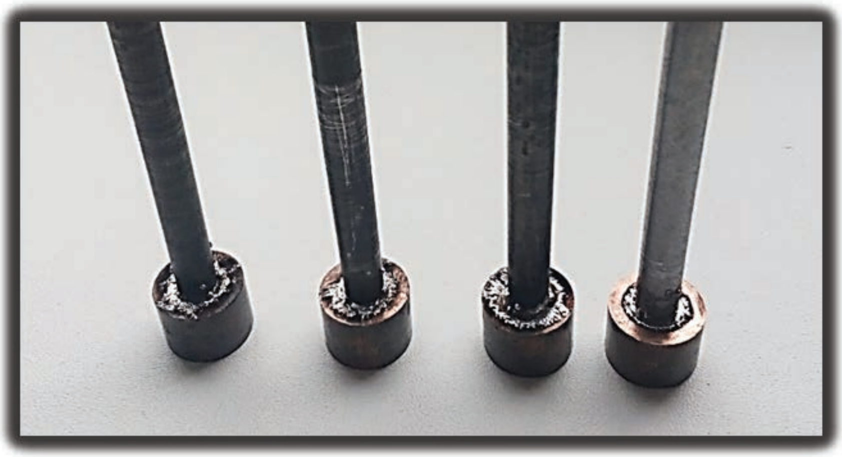

Fig. 2. Experimental samples of diamond heads with a diameter of 12 mm, made using the method of capacitor welding

Results and discussion

The condenser welding mode was selected visually, according to the welded joint appearance. At voltages of more than 110 V, a significant splashing of liquid metal from the weld was observed, and at lower voltages, on the contrary, insufficient melting of the welded product surfaces was observed and void formation along the welded joint edges between the main and intermediate cases occurred.

As it is known [27], the condenser welding allows obtaining sufficiently firm joints between dissimilar metal materials due to the small thickness of the melted layer and the lack of dissimilar metals mixing due to the short duration of the arcing.

However, when welding carbon steel products, the strongest and most reliable joints, in the case of condenser butt welding with arc ignition and reflow of the jointing surfaces, are provided when the jointing products are made of low-carbon steels [27, 32]. An increase in the carbon content in products to be weld leads to a decrease in strength properties, which is usually associated with brittle structural components appearance in the welded joint in the form of martensite and residual stresses. Moreover, as the authors' simulation results and experimental data show [33], it is not possible to completely avoid the formation of voids in the weld area during condenser reflow welding. Indeed, as can be seen from the photo of the longitudinal macrotemplet (Fig. 3), cut from the diamond grinding head under study, there are discontinuities in the area of the welded joint, reaching in our case 0.15×0.5 mm. The availability of discontinuities and residual stresses in the weld is one of the reasons for the welded joint low strength between the cylindrical case made of quenched carbon steel and intermediate case made of low carbon steel. For example, the joint efficiency between a case made of quenched steel 45 and an intermediate case made of low-carbon steel of St.3 doesn't exceed 300 MPa, and fracture is usually brittle along the weld. Therefore, in order to remove residual stresses and increase resistance to brittle fracture, the investigated grinding heads after condenser welding of the quenched case were subjected to low tempering at a temperature of 240 °C, for 2 h.

The results of tests for the strength of the joint of the shank with the diamond-bearing part under tension of the studied samples of grinding heads are shown in the table (Table). The lowest joint efficiency in tension have diamond grinding head, made using traditional technology, as in this case, the part of the body (shank) inside the diamond layer has a smooth surface, and the joint efficiency is secured due to the cohesive forces formed between the copper-plated surface of the housing and the binder metal in the result of sintering and hot extrusion.

The investigated diamond grinding heads, joined to the case made of quenched carbon steel using the method of condenser welding, have a higher tensile strength between the case and the diamond part than diamond heads joined to the case made of R6M5 steel using a standard technology as a result of sintering and hot pressing. Such a difference in joint efficiency is due to the fact that in the manufacture of

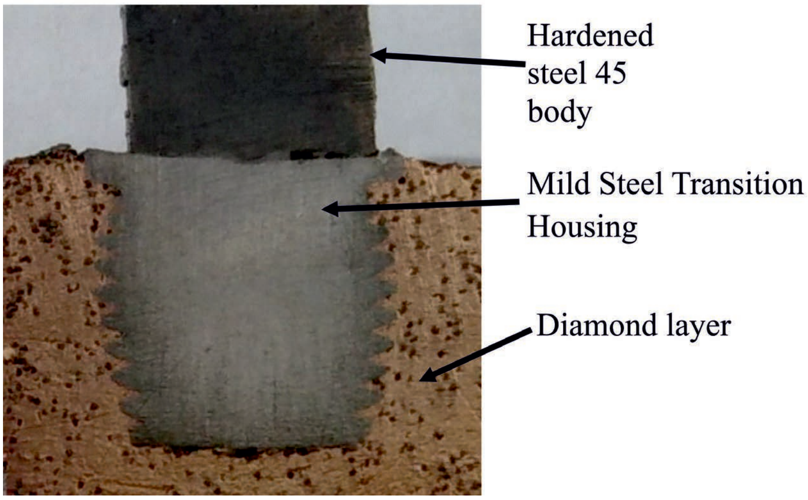

Fig. 3. The macrostructure of the welded joint area
of the investigated diamond grinding head

Dependence of the strength of the connection of the shank 6 mm with the working diamond layer of the grinding head 12 mm on the connection method and body material

Method of the case bonding to the working diamond layer	Case material	Case hardness after quenching and (tempering), HRC	Tensile joint efficiency between the case and the working partsв, MPa	Note
Traditional diffusion sintering technology	High-speed steel R6M5 (prototype)	62(55*)	200 ± 20	Separation between the case and the working diamond part
Condenser welding using an intermediate case	Steel U8	62(56)	350 ± 35	Weld rupture
	Steel 60	61(55)	400 ± 36	Weld rupture
	Steel 45	54(48)	500 ± 30	Weld rupture
	Steel 35	45(42)	520 ± 35	Weld rupture
* – hardness of the case made of steel R6M5 after sintering and hot pressing at 700°C				

investigated diamond heads according to our proposed method, a copper-plated steel screw stud 3 (Fig. 1) is pressed into the diamond layer, which provides both significant mechanical adhesion by the diamond layer and greater interatomic adhesion due to the larger diffusion sintering surface to a metal bond.

The highest values of joint efficiency, provided by the case condenser welding to the working diamond part, are observed in the grinding heads with shanks made of medium-carbon steel of 35 and 45 grades. The tensile joint efficiency between the case made of quenched steel 45 and the M6 stud pressed into the diamond part is 500 MPa, and the joint efficiency limit between the case made of quenched steel 35 and the M6 stud is 520 MPa. At that, it is important that the joint efficiency between the case and the diamond part in these grinding heads is not lower than the intermediate case tensile strength, which is a welding stud of 4.8 strength class, which, as noted above, in accordance with the requirements of GOST should not have a strength limit below 400 MPa.

As can be seen from the table, a tensile fracture of the investigated grinding heads, manufactured using the method of condenser welding, occurs in the region of the weld. Measurements of the shank made of steel 45 weld joint microhardness with an intermediate case in the form of a screw stud show (Fig. 4) that the screw stud material has a microhardness of 200 HV 0.05, and the case (shank) of a tool made of steel 45 after quenching and tempering has 500 HV 0.05. The weld joint region thickness, including the heat-affected zone, where the tool case hardness decreases (Fig. 4), is 0.3...0.4 mm.

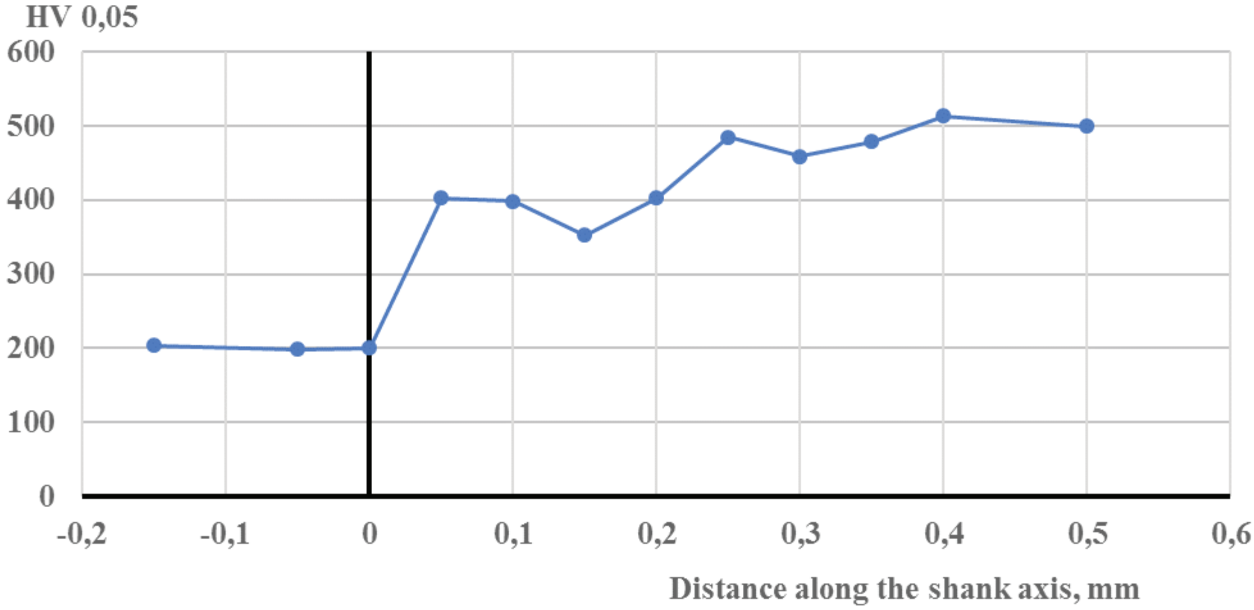

Fig. 4. Change in microhardness in the area of the welded joint of the body with the transition body of the diamond grinding head

The efficiency of the investigated grinding heads with a shank made of thermally strengthened steel 45 was checked by comparative tests when processing plates made of hard alloy T15K6 on a milling and engraving machine of “CARVER Mini-0609” model. Tests were carried out under the following conditions:

- head rotation speed of 24,000 rpm;
- cutting depth of 0.04 mm per double stroke;
- longitudinal feed speed of 0.5 m/min;
- head stroke length of 15 mm;
- test duration of 60 min;
- without the use of coolant.

All the investigated samples of grinding heads in the amount of 3 pcs. with a shank made of heat-treated medium-carbon steel 45, were manufactured according to the above technology using condenser welding and one grinding head with a shank made of steel R6M5, was manufactured according to the standard technology, passed these tests, retaining further operability.

Conclusions

Thus, the results of comparative studies allow arguing that the joint efficiency between the shank and the working diamond part according to the proposed technology is superior to similar characteristics of the joint efficiency between the shank and the diamond layer of grinding heads obtained using the standard bonding technology.

The proposed technology of diamond heads manufacture increases the joint efficiency between the case and the diamond working part, reduces the cost of manufacturing grinding heads due to the use of quenched medium-carbon steel as the tool case material instead of high-speed steel grades, the technology is simplified and a possibility of automating the manufacture of tools appears.

Comparative operational tests of the grinding heads show a comparable service life with traditional tools. It is not possible to completely avoid the formation of voids in the weld area during condenser reflow welding. This indicates the possibility of using medium-carbon quenched steel with a hardness of 45...55 HRC as a shank material.

All this indicates the possibility of using medium-carbon quenched high-quality steel with a hardness of 45..55 HRC as a shank material and the use of the proposed technology for manufacturing diamond grinding heads on a metal bond, which will increase the joint efficiency between the case and the diamond working part and reduce costs and simplify tool making processes, thereby increasing the diamond end abrasive tool efficiency.

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Conflicts of Interest

The authors declare no conflict of interest.