Waste Cutters Utilization in Underground Coal Mining

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With increasing depth of underground mining and complexity of mining and geological conditions, the number of wasted cutting tools increases. Increased rock hardness in coal-, ore-, salt-, gypsum and other mines leads to an increased number of cutters worn out during the operation of shearers and road headers. A lot of wasted cutters are piled up in mines. Research has shown that mainly a cutter head is worn, and up to 70-80% of the tool retains its shape almost unchanged. Reusability of a significant part of wasted cutters is proved. Design of a composite cutter providing its multiple uses and reducing wastes in underground coal mining is presented. An engineering solution on remanufacturing and reusing wasted cutters piled up in mines is suggested. This requires pre-sorting of waste and selection of suitable cutters to repair. Then, a deformed head of each worn cutter is removed, and an axial bore is drilled in the cutter tail. A replaceable cutting head is turned from a metal bar and is equipped with a carbide tip. The operating head is secured into the holder made of the worn-out tool. A shape and a mechanism of the operating head attachment ensuring the reliability of the connection are designed. Such cutter is reusable and can be mounted on combines. Industrial tests of the composite cutter in mines showed good results: one holder served as the basis for the operation of nine operating heads, and it was not required to purchase nine traditional full-size cutters. The solution reduces metal consumption by five times and ensures a significant reduction in purchase costs (up to 1.5-1.7 times), thus improving the resource efficiency of coal mining.

***Key words:** mine, combine, cutter, waste, operating head, utilisation, resource efficiency*

Introduction

Mining industry belongs to the most resource-intensive industries in the world. As the depth of mining operations increases and the geological conditions become more complex, the problem of resource-efficient mining technologies and processes becomes increasingly important (Umnov, 1995; Miroshina, 2002; Komarov et al., 2007; Troubetzkoy, 2011).

Road heading and extraction of minerals from salt, gypsum, coal, and other mines are currently carried out mechanically by means of tunnelling and mining combines. Actuating devices of these machines have the form of crowns, bars and screws equipped with tangential rotary cutters (TRC) (Fig. 1). Tangential rotary cutters have replaced radial cutters due to some advantages, such as self-sharpening and relatively longer life, lower energy intensity of failure, easy installation and operation. Further improvement of actuating devices and cutting tools is a subject of many research works all over the world. There are studies on the effect of cutters' inclination on their penetration into the rock mass (Jonker et al., 2014; Fu et al., 2015). Dewangad and Chattopadhyaya (2015) studied how the amount of the broken coal and cutter temperature correlate with penetration depth. Works by Dewangad et al. (2015) and David (2014) are devoted to the influence of the elemental composition of the tip material on its durability in rock and coal breaking, as well as to the mechanism of degradation of tungsten-cobalt alloy in contact with the rock. The research of Bolobov has shown that the mining tool wear rate is influenced by the hardness of rocks, their abrasivity and the structure of mineral grains (Bolobov et al., 2015).

Chinakhov et al. (2011) and Prokopenko et al. (2016a) propose to prolong the tool life by strengthening cutter heads with extra armouring and hard-facing steel bodies. Technical solutions changing the geometry and the shape of cutter heads to increase their breaking capacity are presented in a number of proceedings (Fader and Lammer, 2011; Greenspan et al.,. 2014; Sarwary and Hagan, 2015). Papers by Tompson and Tank (1990) and Liu et al. (2015) study an impact of water supply in the breaking area on the efficiency of rock breaking.

Researches by Khoreshok et al. (2012), Bolobov et al. (2012), Kolesnichenko et al. (2012) present test results of tangential rotary cutters operating on mining machines in the Kuzbass mines (Russia) and recommendations to improve their design. Advanced designs of cutters with replaceable reinforcing tips, removable heads, secured shanks, etc., are offered by the following scientists in scholarly proceedings (Bell, 2013; Bookhamer and Chad, 2014; Monyaket al., 2104; Parrott, 2014; Prokopenko et al., 2015, 2016b, 2017). The use of ellipsoid cutter tips instead of conical ones is discussed in the work Khoreshok et al. (2013).

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A considerable disadvantage of the TRC is that they are not reusable. Nevertheless, effective solutions on the further use of worn out cutters have not yet been proposed. As a result, after some (often inconsiderable) wear of the body, a tool falls into the category of waste products. Such cutters are either thrown away straight in the face or lifted up to the surface, where they are stored in open mine warehouses for a long time rusting and depreciating in large quantities. At best, they are sold to metallurgical plants as scrap to be melted. These facts stipulate low resource and cost efficiency of rock-breaking tools in mines.

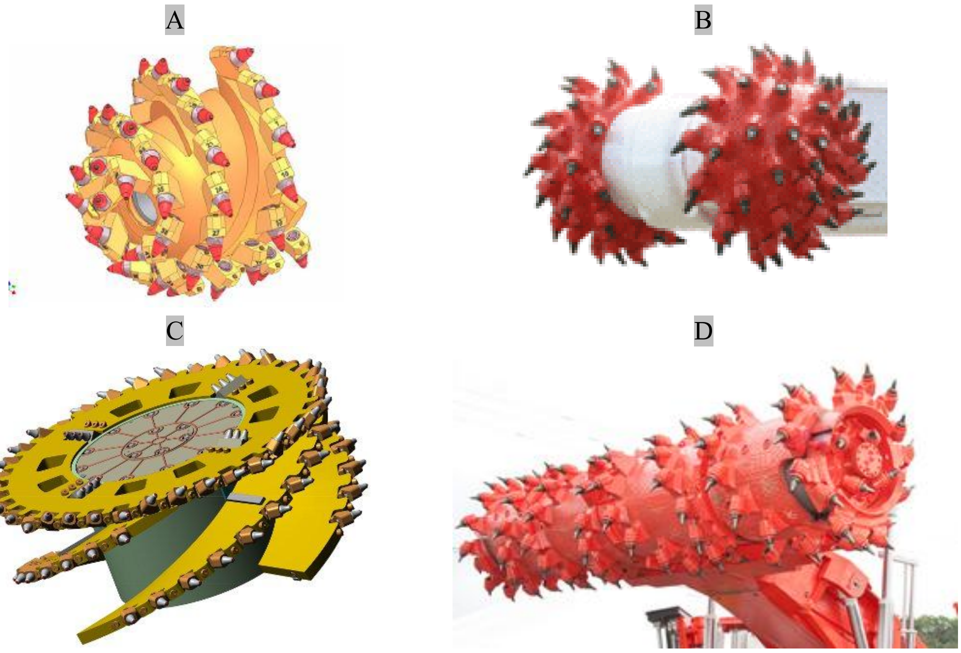

Fig. 1. Actuating devices of mining combines:
A – Direct-axis crown; B - Cross-axis crown; C - screw; D – bar.

Materials and methods

Cutters mounted on tunnelling and mining combines in the Kuzbass coal mines were used as the object of the research. Surveys were carried out in mines of the northern, central and southern parts of the coalfield with different mining and development conditions. Structurally a tangential rotary cutter is a metal holder with a cylindrical shank and a conical head with high-strength wear-resistant alloy cutting tool which is fixed to the edge. The holder shank is mounted in the cutter holder of the actuating device and fixed firmly to prevent spontaneous loss of the tool. Special metal locks or plastic half-rings mounted on the shank groove are used as clamps.

Actuating devices usually have 28-56 cutters or more, and combines have as many as a hundred and fifty cutters. In general, all currently used cutters for tunnelling and mining combines are similar in design. They differ only in size and shape of heads and shanks (Fig. 2).

Fig. 2. Model range of cutters for various combines.

Rock-breaking is accompanied by a gradual abrasion of the tool reinforcing element. The tool life is determined by several factors, the main ones being the hardness of the rock broken, strength and quality of the tool metal, operational condition of the tool holder, fastening security, a driver's qualification. In the Kuzbass mine, cutters serve from a few weeks (for coal) to several hours (for durable sandstone). The average consumption rate of cutters for one combine is 200-300 units per month, rising up to 150-250 pieces per day when breaking a layer of hard and abrasive rock. One 1 kg cutter costs 800-1,000 rubles that is comparable with the cost of 1 ton of coal mined.

According to the service instructions, a cutter with a worn out carbide tip cannot be used any more as it is not able to break the rock, and it should be replaced with a new one. Fig. 3 shows worn out cutters demounted from various combines in different mines.

Fig. 3. Wasted mining cutters after rock breaking in the Kuzbass mines.

Wasted cutters from seven Kuzbass mines were surveyed. Their size was measured after the operation; their shape and wear pattern were assessed. In total, about five hundred cutters were surveyed.

For justification of the proposed tool dimensions, the finite element method was applied to make computations in SolidWorks Simulations software which is used to analyse the stress-strain state of structures, including mining machinery (Buyalich et al., 2016; Khoreshok et al., 2016).

The results of computation were verified in the course of industrial tests in "Pervomaiskaya" coal mine (RF, Kemerovo region) on road-header КСП-35 while driving a roadway of 16.5 m^2 cross-section, along stratum No24 with depth of 1.03 m and average rock hardness f = 4-6 (8) on the Protodyakonov scale.

Results and Discussion

The analysis of wasted cutters size and shape indicates that up to 70-80 % of the holder often remains practically unchanged. Only the front part of cutters is subjected to abrasion. However, further use of cutters without the carbide element is prohibited due to a sharp increase in cutting force, intense frictional sparking, and increased loads on the combine transmission. Demounted and wasted cutters are often worn out no more than 10-15 %. In this case, up to 85-90 % of the cutting tool made of high-strength and expensive steel goes to waste. The mass of a new tool is 1,050g, and 890-945g of it is wasted.

Remanufacture of wasted cutters for further use can help to improve the resource efficiency of mines. Studies of the pattern and extent of cutters wear as well as of their design features make it possible to recover a significant part of cutters wasted during coal mining. For that purpose, it is proposed to sort the wasted cutters and select those with wear degree which does not exceed 50 % of the initial length of the head. According to expert estimations, the share of "recyclable" cutters can be up to 70-80 % or more of the total amount of waste. After that, it is required to remove the front deformed part of the cutter leaving 50-70 % of the initial length of the head intact. In the remained part of the head, a slot should be drilled along the axis, its length l and diameter d corresponding to the cutter size (Fig. 4).

After that, an operating head to the holder which follows the shape of the initial head is turned out of a metal rod. It is tipped with carbide and subjected to thermal treatment. The operating head length and shape must restore the original settings of the head. The operating head should have a shank to be placed in the holder slot. An expanding half-ring is fixed in the groove of the shank. It arches into the slot groove and fixes the operating head on the holding head without preventing their mutual rotation. Such cutter can be reused several times, which is an important advantage alongside its low cost. For reuse, a worn-out head can be easily replaced with

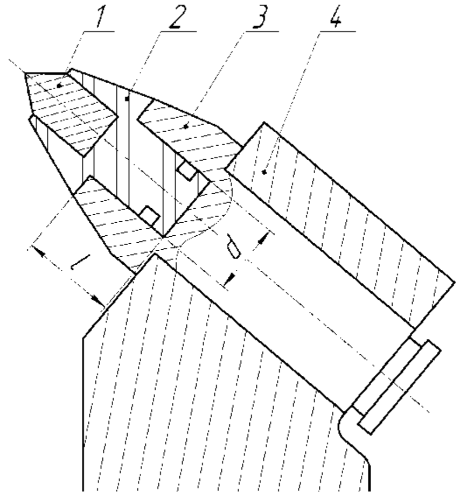

Fig. 4. Construction of composite cutter:
1 – hard-alloy tip; 2 - operating head; 3 - holding head; 4 - cutter support.

a new one. Besides, an extra rotary group (in addition to the cutter holder shank) facilitates rotation of the cutter and ensures even wear, which increases its service life.

Designing a composite cutter structure required verification of operating head key design parameters, namely diameter **d** and length **l** of the shank. The construction of cutter РГП 33-87-70/16M mounted on road-header КСП-35 was chosen for verification of operating head shank (OHS) parameters. These combines are widely used in the Kuzbass coal mines for the road heading in rocks of medium and high hardness. The actual cutter dimensions were used to make a geometric model and perform strength computations using the finite element method in SolidWorksSimulations software.

The aim was to compute diameter **d** and length **l** of the operating head, which would provide maximum structural strength during operation of cutters. A series of computations were performed to analyse how the dimensions effect on the stress-strain state of the structure. During analysis, the shank diameter **d** was varied in the range of 16 to 34 mm in increments of 2 mm; shank length **l** was varied in the range of 17 to 29 mm in increments of 2 mm.

Reduction of maximum stresses in the capacity size of the operating head and the holding head was taken as a criterion for selection of optimum dimensions. "Fixed" fastening of the lower edge of the support was assumed as the kinematic boundary condition. This type of fastening limits linear displacements along three coordinate axes, taking them equal zero (Fig. 5).

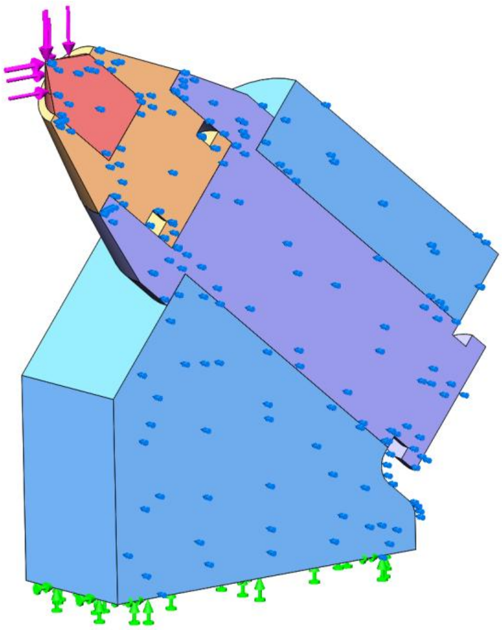

Fig. 5. Design model of the composite cutter with applied loads and fastening types.

Since it was a geometrical model, boundary condition "Symmetry" was assumed due to properties of detail materials and loads and fastening types being symmetric relative to the vertical plane. The geometric model was dissected by a plane of symmetry; the kinematic boundary condition prohibiting displacement along the normal to the cutting plane was assumed for the cross-section surfaces. It reduced the size of the problem and removed irrelevant degrees of freedom of the components, whereby the density of the finite element mesh and the computational accuracy were improved.

The hard tip operating surface was loaded with cutting force Pz = 10,476 H and Py = 2931 H, which corresponds to the conditions of cutting rocks of hardness f = 5 units on the Protodjakonov scale (Aksenov et al., 2013). Since the computation was performed for the composite unit, contact interaction conditions for contacting detail faces were described. Contact condition "Related" simulating solder connection was assumed for hard tip surfaces. Interaction of other details was described with "No penetration" contact condition, excluding occurrence of component interference, but conceding backlashes. Contact condition was used with option "surface to surface". This type of contact facilitates maximum accuracy when solving a contact problem with interacting smooth curved edges, but it requires the greatest computing resources.

A mesh with parabolic finite elements (FE) in the form of tetrahedrons was used when sampling the geometric model. The parabolic FE provided a better description of the model geometry and increased the accuracy of computations due to more points if compared with the linear FE. Mesh settings: FE size - from 1 to 5 mm; element size increase ratio - 1.6; automatic condensation of the mesh was not used. FE size was chosen in such a way that further mesh condensation would have no significant effect on computation results.

For computations, "FFEPlus" solver was applied, which uses advanced matrix reordering, being more efficient for large problems. As a part of the study, various computations with changing OHS diameter and length were analysed. Computations show that geometric parameters d and l affect the distribution of equivalent stresses by Mises criterion in the cutter elements under operating loads. Fig. 6 shows a diagram of stresses for a structure with d = 28 mm l = 23 mm. It shows the distribution of stress magnitudes over the support body, holding head and shank, as well as over the removable head with the hard tip in the range of 0-100 MPa. The greatest stresses occur at the cutting face of the tip (up to 100 MPa), the smallest - in the support (5-35 MPa). A high-stress zone (60-80 MPa) appears where a removable head is fixed in the retaining head and opposite to the direction of the cutting tool motion.

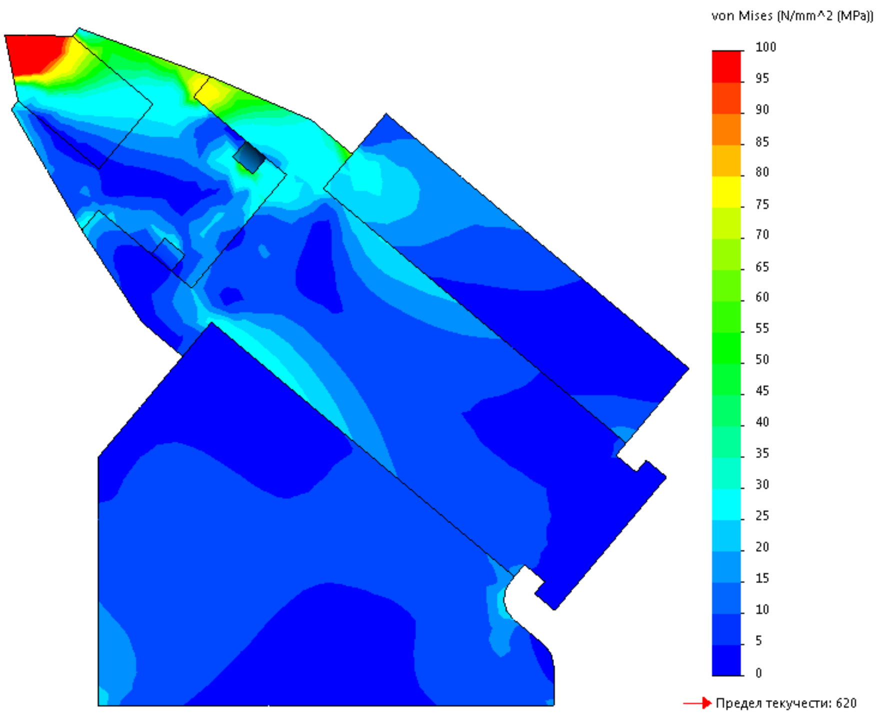

Fig. 6. Distribution of equivalent stresses by Mises criterion in composite cutter elements.

The results of computations for 70 variants of the original data are presented in graphs (Figs. 7 and 8). Ratios of holding head maximum stresses to shank diameters for its various lengths are analogous to minimum stresses of the shank with diameters ranging from 18 mm to 22 mm. Outside of the specified range, an increase of maximum stresses is observed. Minimum stress is 68 MPa for shank diameter d = 22 mm and shank length l = 29 mm (Fig. 7).

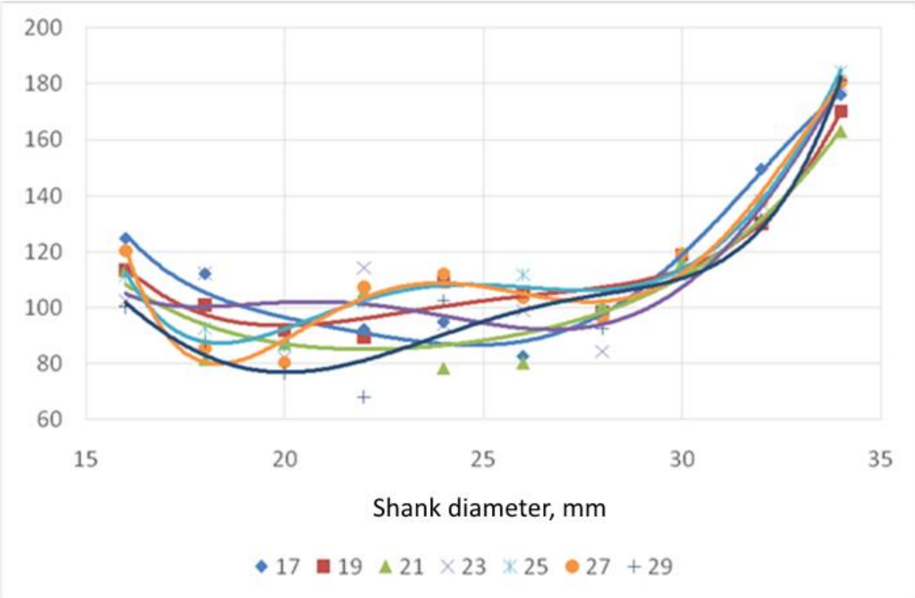

Fig. 7. The relationship between holding head maximum stresses (MPa) and shank diameter d if l=17, 19, 21, 23, 25, 27, 29 mm.

Fig. 8 shows similar curves for the maximum stresses in the operating head. Although relationships have more complex and heterogeneous nature, there is a common minimum for all lengths in the range of shank diameters from 28 to 32 mm. The minimum stress is equal to 75 MPa for diameter d = 28 mm if shank length l = 17 mm.

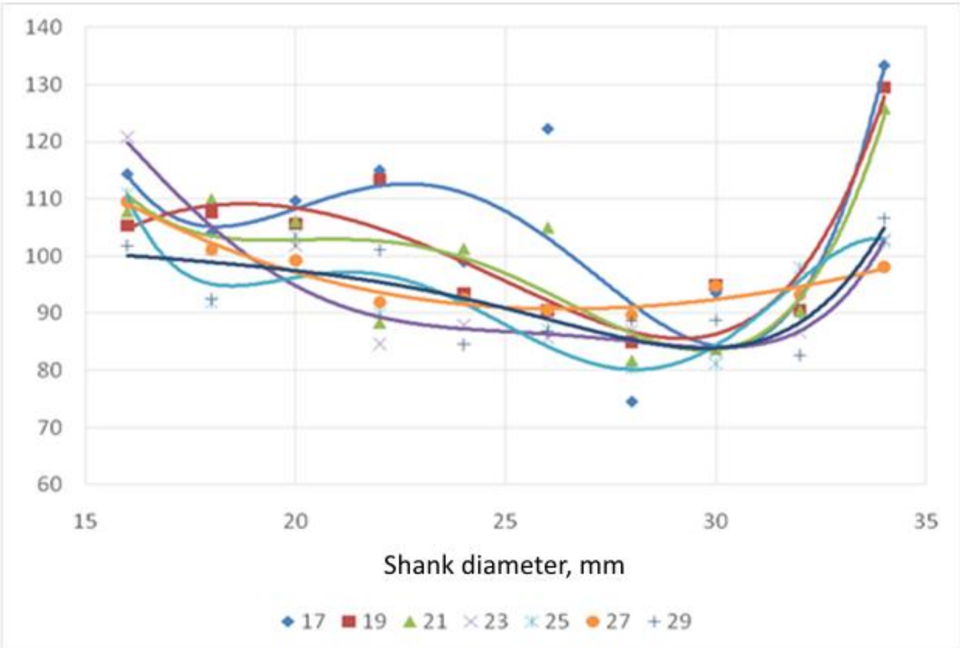

Fig. 8. Relationship between operating head maximum stresses (MPa) and shank diameter d if l =17, 19, 21, 23, 25, 27, 29 mm.

Since the areas of minimum stresses for the holding head and the operating head do not coincide, a graph of arithmetical averages between corresponding points of two previous graphs (Fig. 9) is proposed for more comprehensive evaluation. The graph identified the minimum value corresponding to all size variations, namely, d = 28 mm l = 23 mm.

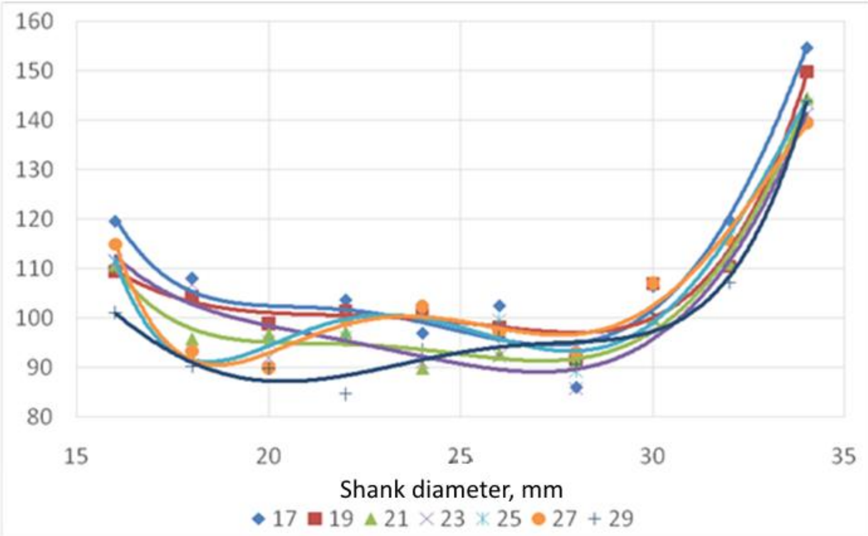

Fig. 9. Relationship between stress arithmetical averages (MPa) and shank diameter d if l =17, 19, 21, 23, 25, 27, 29 mm.

Composite cutters with the optimal settings were manufactured in accordance with the results of the computation. Fig. 10 shows the holder of a worn-out cutter and the process of installing a new operating head into it.

A **B**

Fig. 10. Composite cutter remanufactured from a worn-out one
A – holder made of waste; B – installing a new operating head into it.

The operating head shanks were 28 mm in diameter and 23 mm in length. Sample cutters manufactured in accordance with the recommendations were tested at KSP-35 road-header in "Pervomaiskaya" coal mine in 2014. Two composite cutters were installed in the second row of the crown-type actuating device. The operating heads were replaced on reaching wear limit. In total, 18 operating heads were tested. Wear was even, without breakdowns. Heads lifetime was 3-4 weeks; that corresponded to the road heading 60-90 m long.

Industrial tests of the remanufactured cutters in the mine showed good results: one holder was used as the support for 9 cutting heads, having replaced 9 conventional tools. Calculations show that 9 operating heads require 1,935 g of metal and replace 9 conventional cutters of 9,600 g. Thus, metal consumption is reduced up to 5 times. Purchase costs are reduced 1.5-1.7 times. The current annual consumption of combine cutters in the mines of Kemerovo region is about 200-300 thousand pieces (200-300 tons), the utilization of waste reduces the need for metal up to 40-60 tons per year and save up to 75-113 mln rubles per year.

Conclusion

As a result of the research, the organisational and technical solution to improve the resource efficiency of cutting tools for mining combines is suggested. It is proposed to remanufacture waste combine cutters by means of reconstructing and equipping them with changeable operating heads. A composite cutter using a holder from a wasted cutter as the support and a new cutting head is designed. A shape and a mechanism of the operating head attachment ensuring the reliability of the connection are designed.

Computer modelling in SolidWorks Simulation software sets optimal values of OHS diameter and length, which provide the highest strength characteristics of the cutter body during operation in rocks of hardness f=6-8 on the Protodyakonov scale. The lowest stresses are observed in the body of cutter РГП 33-87-70/16М if OHS diameter is 28 mm and the length is 23 mm. The operating heads with the specified parameters were tested on cutters of КСП-35 road-header operating in the mine. The test results proved the validity of the specified parameters. The heads operated without any damage until worn-out evenly. The tests show that the holder can serve as a basis for the operation of nine operating heads replaced subsequently.

Thus, the holder made of waste can be used multiple times. It ensures a significant reduction in purchase costs (up to 1.5-1.7 times) and metal consumption up to 5 times, as well as increases resource efficiency of coal mining.

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