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FEASIBILITY OF LEAN PRODUCTION CONCEPT AT INDUSTRIAL UNDERTAKINGS IN KUZBASS

The article discusses feasibility of smart and efficient resource use in the machine works–mine cluster based on the concept of lean and low-waste manufacture. Products of the machine works (pumps, coal pumps, fans, winch arrangements, buckets, conveyors, rock-breaking tools etc.) for the mining industry feature a high resource consumption and a rather short life. The latter is governed by a set of specific factors, namely: rock pressure, rock bursts and gas outbursts, high gas and dust content of air, higher moistness of underground openings and rock mass, high abrasivity of water, air, rocks etc. As a consequence, machines, mechanisms and tools go unserviceable very fast and pass into waste. At the same time, if treated sparingly and economically, many types of production waste have a high chance of recovery up to the level of good condition and return to a production cycle, while some waste items can be brought to even a better condition with new properties. To this effect, cyclic technologies of higher resource-saving level are required. The feasibility of waste recycling and resource efficiency enhancement in the machine works–mine system is discussed as a case-study of a rock-breaking tool. The proposed structural properties and technological capabilities form a three-level waste recycling system for shearer picks, which provides conditions for prudent handling of metals involved in the process of rock fracture–steel and hard alloy. A long-term life cycle of the metals in the mining industry is ensured, at the decreased metal losses, increased level of non-waste operation of coal mines, and at the better performance of the picks. Development of new designs and technologies by mechanical engineers in cooperation with mining engineers makes the low-waste mining industry in Kuzbass realistic.

Keywords: *ongwall shearer, worn-out cutter pick, waste, utilization, downcycling, recycling, upcycling, system, modular cutter pick, module, hard alloy, resource saving*
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Introduction

It is already a few decades that advanced world's economies have been adhering to the paradigm of saving production and effective resource management [1–7]. This is directed by the fact that the responsible national societies become increasingly aware of the exhaustibility of the Earth's resources, improve their environmental legislation and activate efforts of environmental agencies while business starts to comprehend benefits of husbandry and saving use of resources in production processes. The low-waste and resource-saving economic model persistently expands and deepens, involving new countries, industries and scopes of human activities [8–10]. Russian coal industry that participates in the tightening business competition in the global energy market is unable to avoID the general trends of development. Holding and consolidation of the attained market positions dictates that Russian coal companies and mines master at the earliest possible time the advanced low-waste technologies to reduce resource

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intensity and cost of coal production, and to raise competitive ability of coal products [11–15].

Aiming to improve wearability and destruction efficiency of rock-cutting picks, Russian scientists examine Russian and foreign technologies of cutting tool manufacture, and also their influence on thermal treatment quality and on hardness of the tools [16]. The scope of the investigation encompasses application conditions, and the rates and types of wear of the tools [17–19].

Foreign scientists search for the improved designs of cutter picks and their components [20–22]. Wide-range studies are carried out using various bench testers to investigate effects exerted by setting angles of cutter picks, cutting depths and velocities, water feed ahead and behind the tool on sizes of broken rock particles, temperature of the tool and its deformation rate [23–25].

The loads applied to cutter picks and transmissions of cutting drums during cutting of hard inclusions in coal seams and at changes of cutting modes were analyzed [26, 27]. Indian scientists investigated the types of wear of tips of cutter picks, with identification of cracks, caverns and the effect of sanding [28].

An integrated research was undertaken to study the influence exerted by: diameters on wear rates of carbide inserts [29]; hardness of rocks on service life of cutter picks and shearers [18]; amount of alloying elements in steel on its abrasive wear [30]; uniformity of thermal treatment of cutter picks and application of high-temperature thermomechanical treatment on wear rate and service life of cutter picks [16]; shape of indenters on durability of tools [31].

Although numerous studies aimed at improvement of design and manufacture technologies of cutting tools, elongation of their service life, modeling and optimization of working conditions etc., worn-out picks of heading and coal cutting machines yet lack attention. There are only a few publications on finding ways of recycling of high-quality metal rejects. The goal of this article is to review the advanced trends in resource-saving in industry, and in potential effective recycling of waste represented by worn-out picks of shearers toward extension of service life of functional cutter picks with gaining additional benefits for the industries and society.

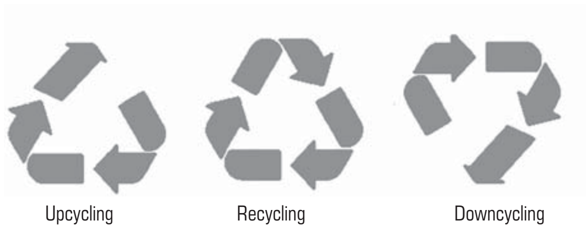

Fig. 1. Trends of waste re-use

a *b*

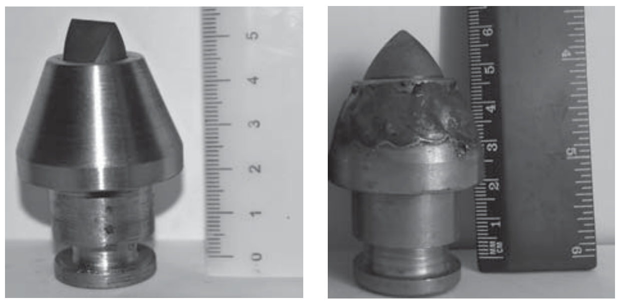

Fig. 2. Cutting module with blade tip (*a*) and with built-up armor shell (*b*)

Research methodology

The issue of industrial waste recycling was examined using Russian and foreign literature sources and Internet resources, as well as field studies implemented by Russian coal miners. New designs of cutting tools were developed using the methods of heuristics, brain storm and finding ideas and things [32–34]. The lab-scale investigation of spark formation used a test bench of VostNII Science Center and samples of cutting tools employed in underground coal cutting in mines in Kuzbass. Operability and efficiency of recycled designs of cutter picks was tested in laboratories and in some Kuzbass mines.

Results and discussion

The use of industrial waste, depending on its processing degree, follows three strategic directions: recycling, downcycling and upcycling. Recycling is waste conversion without the loss of quality; downcycling is waste conversion with the loss of quality; upcycling is waste conversion into something more effective and beneficial, i.e. with the quality improvement. These technological approaches are depicted in **Fig. 1**.

At the present day, Kuzbass mines regard cutter picks prevailingly as expendables. Managerial control in this sphere is poor, the efficiency monitoring is shallow (at the level of better and worse), no cost per tool is calculated and applied, no targets at delicate use of tools are set by management, and the saving attitude lacks encouragement and application. The result is high rejects of cutting tools at almost zero re-use.

There are only a few mines known to collect worn-out cutter picks of heading and shearing machines, and to shipping them as second-hand materials for remelting at metallurgical plants. Such way of use means termination of existence of former tools and fits the trend of downcycling. Mostly, miners replace worn-out picks and throw them away right in the face area, which points at the prevailing mode of mismanagement and diseconomy at the present-day coal mines. An average-capacity mine spends 15–20 thousand of cutter picks annually. In this case, owing to structural peculiarities of actual cutter picks, after wear out of a carbide tip (which is 10–15% of the length and mass of the tool), the rest part (85–90%) becomes the reject too. In the meanwhile, such waste are the metal goods with high level of treatment, having the wanted shape and almost free of wear.

The recent modular design of tangential rotary picks (TRP) proposed by mechanical engineering scientists [35] offers a new potential for redesigning actual one-piece body tools after their wear toward their further utilization using a more efficient trend than downcycling. The modular pick design includes a holding module composed of the shank and a part of the head as in a traditional cutter pick. The other part of the head and the carbide tip are the replaceable cutting module. Coupling of the modules is executed with the help of a cylindrical axial adapter.

Such modular structure is manufacturable by means of using a worn-out pick for manufacture of a holding module or a few cutting modules. The modules are manufactured using materials and technologies which are currently in application at machine building plants. Efficiency of the composite cutter pick is ensured by long-term operability of the holding module at periodic replacement of the depreciating cutting module. Industrial tests showed attainability of 8–10 work cycles of a modular cutter pick until its main part breaks down [36]. Configuration and technology developed at Power of Siberia Machine Works JSC ensure recycling of conventional picks in rock breaking Metal rejects return to the initial rock destruction technology and continue to be used as cutting tools.

After a holding module experiences unacceptable deformation, it goes to scrap. The worn-out cutting modules, discarded one-piece body cutters unsuitable for redesign because of their heavy wear, as well as metal chips formed during reworking can be re-used. The proposed waste treatment technology ensures complete use of metal the cutter picks are made of in the recycling and downcycling directions almost without material losses. Moreover, many-cycle recycling of the most portion of metal is achieved.

It is even possible to reach longer durability of metal through higher quality thermal treatment of cutting modules. This possibility is conditioned by the smaller (5 times less) mass of the items to be tempered as compared with the one-piece body cutters. A batch of the cutting modules can be

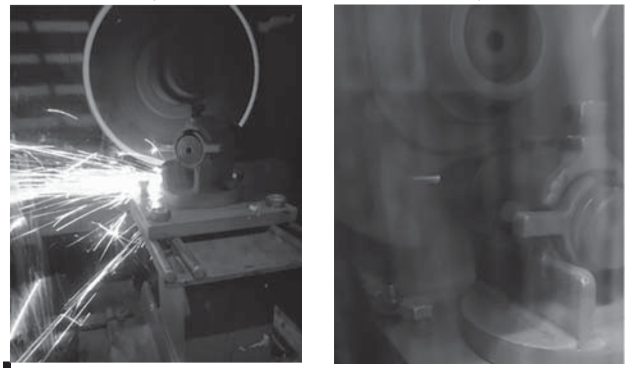

Fig. 3. Sparking of conventional cutter pick (*a*) and armored module (*b*)

Fig. 4. Worn-out picks with remnants of hard-alloy tips

treated in a special thermal mode at the increase of hardness of steel bodies from current 45–47 HRC to 50–55 HRC. Such modules have service life 1.5–2 times longer as against the series-produced cutters. The higher quality and improved durability of such items elevates them to the upcycling level.

Detachability of a cutting module from the cutter pick design pushes even farther the limits of upcycling of the rock cutting tool. Replacement of the conventional conical tip of the cutting module by a blade tip gives such cutter pick a higher cutting ability and energy efficiency in rock destruction at the reduced dust formation in the face area (**Fig. 2*a***). The design of the blade tip cutters and their properties are estimated and described by the authors [37].

Coating of the steel body of the cutting module with an armor shell made of hard built-up metal is another upcycling technology (**Fig. 2*b***). High wear resistance of the armor shell extends durability of the module even more and improves its operational life. The full-scale tests of the upcycled cutter picks manufactured from worn-out picks on a shearer in a Kuzbass mine show that the service life of the replaceable armored modules is 3–4 times longer than the conventional picks have. The holding modules after operation for 45 days and cutting of 65 Kt of rocks feature almost no alteration and keep on operating almost in the initial condition. Despite the higher price of the redesigned cutter picks, they are more economical in terms of rock breaking cost.

Fracture of hard rocks by a cutting tool proceeds with abrasive wear and sparking of metal. For eliminating possible explosion of air and methane mixture and to suppress dusting, the cutting tools of mining machines are equipped with the water spray systems. Behind each pickholder on the cutting drum of a shearer or on a drill bit of a heading machine, a high-pressure atomizer is arranged to spray water in large quantities after rock cutting. For instance, on heading machine KP-21 operated in Kuzbass mines, water consumption in face area spraying via all atomizers totals 122 l/min or 40 m^3 per day. As a consequence, broken rocks get over-moist and become a pulp slurry, which makes loading and haulage highly difficult.

Bench tests on a grinding wheel show that abrasive wear of a conventional-design pick with a steel body results in intense sparking. A thick

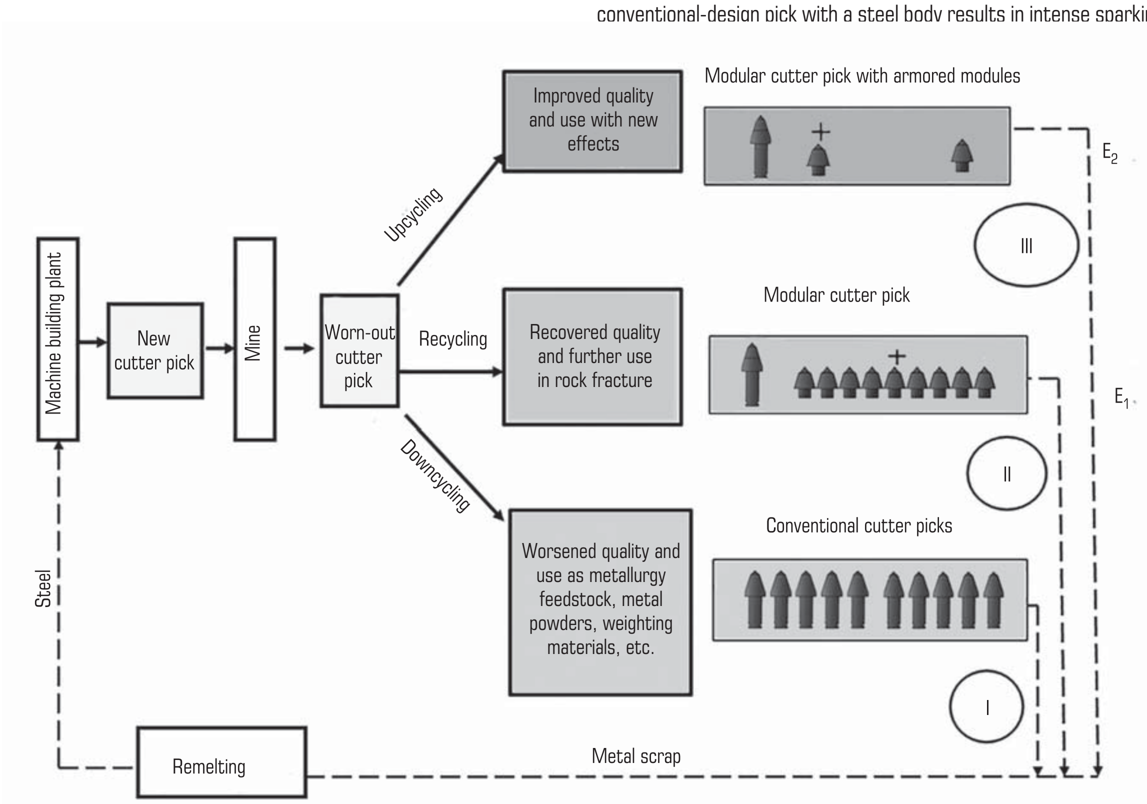

Fig. 5. System of three-level recycling of worn-out cutter picks

beam of violent yellow sparks originates. Trajectories of sparks reach a few meters in length (**Fig. 3**).

Abrasive wear of a module with the built-in armor has another pattern. At the contact of the armor shell and an abrasive, a plume of dark red color 3–4 cm long appears. Sparking is an order of magnitude less intensive. This allows assuming that a tool with a built-in armor shell of a certain thickness is better spark-proof. Accordingly, it becomes possible to reduce water consumption of shearers and to eliminate (or mitigate) a whole range of problems connected with water purchase, conditioning and delivery, with over-wetting of rock mass and its sticking to equipment surface. The new property and additional effects allow placing such re-design tool to the group of the upcycling.

The wear analysis of a conventional cutting tool shows that it often happens that cutters with remnants of hard-alloy teeth fall within waste. This happens owing to different times of setting of cutter picks and due to different wear rates of the cutter picks in different rows of cutting drums, and also because of cyclic inspection of cutting tools by shearers' operators. In order to avoID frequent stopping of shearers and to prevent excessive wear of cutter picks, workers often remove the picks too early. According to the analysis of 58 worn-out cutter picks sent for the re-design, 30 items had a scarce wear of the tips (**Fig. 4**). In the meanwhile, the hard alloy is an expensive material made of such deficient and non-renewable resources as tungsten and cobalt.

The further approach to improving the low-waste use of cutter picks can be processing of hard alloy waste from the worn-out picks [38]. There are many known technologies of the recycling trend for hard alloy waste processing [39–43]. Manufacture of new teeth from recycled hard alloy allows not only saving of the feed material but also helps cutting down electric energy cost of production and reducing emission of carbon dioxide. As Sandvik Coromant engaged in collection and processing of hard allow scrap reports, the energy intake of manufacture of tools from the recycled hard alloy is lower by 70% and the associated reduction of carbon dioxide emission is 40%

The scientists from the Bauman University put forward a new technology for manufacturing cutting tools from recycled hard alloy grade VK6 [44]. This technology uses galvanizing with additional ball milling of powder to a size of 0.6 μm while the regular mixture powders before agglomerating have particles 1.6 μm in size. Replaceable cutting blades made of recycled hard alloy using the new technology were compared with the blades made of hard alloy using a standard technology.

It is found that an average particle size after agglomerating is 2.8 μm in the basic reference variant and 1.8 μm in the recycled material. During agglomerating, the average particle size grows by 3 times in the recycled material and only by 1.5 time in the standard alloy. The experimental alloy is more ordered as compared with the basic alloy structure. The average hardness is 90.5 HRA in the reference blade and 93 HRA in the recycled material blade. Thus, the blades made of the worn-out hard alloy have similar and even better properties than the blades made of the standard hard-alloy powder [44].

The wear resistance tests of blades were carried out by the developers in cutting cast iron CHVG 45 (GOST 28394-89) and steel 45 (GOST 1050-88). It is found that the blades made of the recycled hard alloy have lower wear intensity as compared with the blades made of the basic hard alloy. According to calculations, the cost of manufacture of the replaceable cutting blades from the recycled hard alloy is lower by 27% than the manufacture cost of the blades made of the regular hard-alloy powder [44]. The improved physical and operating properties of the recycled product allow placing the technology in the group of the upcycling approaches.

Generalization of the recent technologies for recycling of worn-out cutter picks yields three basic trends (**Fig. 5**). There are also not only different trends but also different levels of effectiveness: 1) with worsened quality of a recycled item; 2) with the recovered quality of the recycled item up to the initial item; and 3) with the improved quality of the recycled item.

The comparative analysis of cutter picks RSH 35-95L90/19 of JOY 4 LS-20 Longwall Shearer and modular picks REM 35-93-90/19 as the replacement shows that cutting of the same volume of rock mass using these picks features different metal consumptions. Cutter picks RSH are used in downcycling one-use mode I, with rejects in the form of metal scarp to be sent to remelting.

Recycling mode II of metal use allows reducing metal consumption from 15.4 kg to 4.7 kg, or by 3.3 times. Furthermore, effect E_1 includes economic benefit defined by the ratio of prices and amount of purchased items. At the price level by the end of 2021, the cost reduction in purchasing required cutting tools reached 1.4 times.

Even higher effect E_2 is observed in upcycling mode III of using cutter picks. According to the laboratory and industrial testing data, the armor shell of the modular picks extends their service life by 4–6 times as compared with the conventional steel picks. Metal consumption lowers to 2.1 kg, or by 7.3 time. Money saving in purchase of such picks gets down by 3 times. Sparking of the picks and probability of inflammation of air and methane mixtures in mines decreases substantially. The blade tips make it possible to lessen the cutting forces and energy input of coal and rock cutting by longwall shearers.

The three-level system of the utilization options enables delicate handling of steel and hard alloy involved in rock fracture process. Long-term recycling of metals with minimization of their losses in the course of mining is ensured. Some of the proposed technologies of recycling of worn-out cutter picks passed full-scale testing and proved their efficiency.

Conclusions

The modular design of tangential-rotary picks of mining machines affords opportunities for the wide and complete use of the worn-out tools in the process of waste recycling. Such re-use becomes beneficial owing to implementation of the recycling potential of the new design. A holding module made of the worn-out tools can serve for 8–10 cycles, replacing the same number of the conventional picks. It becomes possible to improve the quality of the cutting modules and to give them new and earlier missing properties (energy efficiency, durability, sparking resistance), which elevates the new designs on the upcycling level. Worn-out steel modules, discarded one-piece body cutters, as well as metal chips are suggested to be used in the downcycling mode, by sending them to remelting at metallurgical plants.

The integrated three-level approach to the re-use of the worn-out cutter picks forms conditions for nearly complete return of metal rejects to the production cycle and for their prudent management. The implementation of this approach greatly raises the level of waste elimination in the initial production process in coal mines, improves the economic indicators of the use of cutter picks, and advances coal mines towards saving production and effective resource management.

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