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Technological solutions to extend the operating cycle of tools and industrial machinery

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Abstract

One of the most significant problems that engineers and researchers face is the development of technological solutions to extend the exploitation cycle of tools and industrial machinery. The research shows there are a few possibilities to solve this problem:

1. *Development of new materials of enhanced working characteristics compared to those currently used. An example of this is the introduction of new metals and alloys in the automotive industry, the mining industry, etc.*

2. *Preventive processing of assemblies and parts prior to their use consisting mainly in overlay welding with wear resistant layers or thermo-chemical surface treatment of the parts.*

3. *Recovering assemblies and parts after their resource has been depleted. This is mainly applied in the mining industry, road construction, etc. Worn-out tools are overlay welded and reused. It has been proven that the price of the recovered details is 2 to 20 times lower than that of the new ones. Moreover, it should be pointed out that the recovery saves energy and ore resources and thus a significant environmental impact is achieved.*

This study presents some technological solutions to extend the operating cycle of tools and industrial machines, and namely new types of steel, overlay welding with specially developed electrodes with nanomodifier containing coating, and thermo-chemical treatment.

Keywords: *operational lifetime, new materials, overlay welding, thermo-chemical treatment*

1. Introduction

The development of human civilization is determined by the available raw materials and energy resources on the planet. The interaction between natural and socio-economic factors, as well as the not always reasonable and promising human activity in the XIXth and especially in the XXth century, is the cause for the significant and even threatening depletion of worldwide mineral resources. For example, in study [1] it was pointed out that by year 2025 up to eighty percent of the content of such important elements for industry, such as manganese, nickel, zinc and others in the earth's crust will be depleted. The remaining ores available for use will have a low concentration of useful elements, which will raise the cost of the technologies for their extraction and hence their price on the world market.

Therefore the emerging situation of ever-growing shortage of raw materials raises the problem of developing technological solutions to extend the lifecycle of working tools and industrial machinery. Thus valuable mineral resources will be economized. Another positive effect is the reduction of harmful emission of CO_2 into the atmosphere and also environmental protection.

This study presents some technological solutions to extend the operating cycle of tools and industrial machines, and namely new types of steel, overlay welding with specially developed electrodes with nanomodifier containing coating, and thermo-chemical treatment.

2. Technological solutions

2.1. Development of new materials of enhanced exploitation properties compared to those currently used

2.1.1. Technological background

One of the directions to solve the strategic task of extending the working cycle of industrial machines, tools, etc., is their replacement with the production of new or improved materials with enhanced exploitation characteristics [2]. As is well known, qualitative metallurgy is metallurgy of qualitative steels and alloys. The qualitative metallurgy allows inventing new or improved present steels and alloys with special properties and lowering costs of materials and energy. In this way an indirect beneficial environmental effect will also be achieved. The new steels and alloys should possess the necessary complex of mechanical and physical properties and should be superior to the properties of conventional steel brands. Due to the enhanced mechanical and physical properties on the one hand, and the lower costs for materials and energy on the other, the steels have a resource for long term operation with reduced production costs. Thus improving the quality of the steels [2] by means of invention of a complex of enhanced mechanical and physical properties at lower production costs ensures the long-term operational resource of the products in which the steels are used. All these results have both an economical and an environmental impact.

2.1.2. Theoretical background

Metallurgy under pressure is one of the areas for the development of qualitative metallurgy. This is a method for obtaining new steels and alloys under pressure above atmospheric pressure.The Institute for Metal Science, Technologies and Equipment with Centre of Hydroaerodynamics (IMSTCH-BAS) has created theoretical grounds in the field of alloying with superequilibrium nitrogen concentration and development of new steel grade-high nitrogen steels and technologies for their production by the methods of metallurgy under pressure. The Institute has capabilities and years of experience gained in the field of this method [2]. Using the available laboratory facilities in combination with the scientific and technologic potential of the researchers, various new steel brands and technologies for their production were developed. The technological concepts are based on the original Bulgarian methods for gas counter-pressure casting (CPC) and electroslag remelting under pressure (ESRP). The main advantages of CPC and ESRP for steels production and their alloying with nitrogen include: uniform nitrogen distribution within the ingot since nitrogen is introduced in the liquid bath that is intensively stirred and homogenized; the possibility of precise adjustment of the nitrogen concentration; replacement of the expensive alloying elements, such as nickel; smooth and uniform filling of the mould with melt; because of the technological pressure qualitatively new ingots were produced in comparison with those produced upon conventional casting methods: with improved structure, high density and smaller raiser; versatility in obtaining different brands of alloyed steels, especially in combination with ESRP.

2.1.3. Results

A number of steel brands with increased nitrogen concentration have been developed in IMSTCH-BAS: high-speed steels, hot-die, cold-die, structural, etc. It was proven that the high-nitrogen steels obtained 30% to 150% higher mechanical parameters in comparison with nitrogen-free steels. Thus the cutter instruments made of the high-nitrogen steel type P6A2M5 (analog to P6M5, according to DIN S 6-5-2) were characterised by 38% to 100% higher exploitation parameters [2].

Through modeling of the chemical composition with artificial neural networks a new steel similar to 34CrNiMo6 steel intended for automotive crankshafts was developed and then produced. This steel has mechanical characteristics exceeding the values of the currently used similar steel according to DIN 17200. After mechanical tests it was established that tensile strength and relative elongation of new steel increased up to 18−20% and 10−12%, respectively. This provides a long-term operational resource for the crankshafts made from the newly developed steel.

By replacing the GE 300 steel with hammers for crushing lignite at AES-Galabovo TPP (Maritsa East 1 TPP) selected steel, their exploitation resource was extended by 90−100%. The hammers were cast of steel type GE 300 and were subjected to heat treatment. The demanded tensile strength was Rm = 520−670 MPa and the impact toughness was $KCV \geq 0.31$ MJ/mm^2. Their operational resource is 450 h. The picture in Figure 1 shows the worn-out hammers made of GE 300 steel.

Fig. 1. Worn-out hammers for crushing of lignite made of GE 300 steel

The properties of GE 300 steel, currently used for hammers were investigated. The results were analysed and compared to those presented in [3,4]. A few appropriate types of steel for the manufacture of hammers were selected for work at normal, elevated and lowered temperatures in conditions of impact load (Table 1).

Table 1. Steel brands

Sample number	Steel brand
0	GE300N
1	65Mn4
2	100Cr6
4	55NiCrMoV6
5	32CrMoV33
7	X37CrMoV5
8	32CrMoV33
9	X155CrVMo121
13	X120Mn12
16	34NiCrMoV145

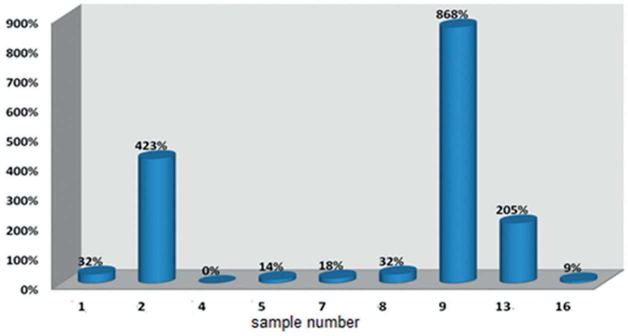


Fig. 2. Relative comparative wear resistance of the steels

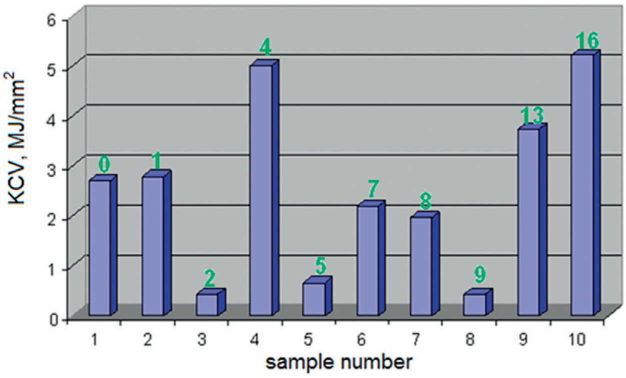


Fig. 3. Impact toughness of the tested steels

After investigation of the exploitational properties of the selected steels, the most promising were chossen: X 120Mn 12, 34 Ni CrMoV 145, X 155CrVMo 121, and 65Mn 4. All these steels had higher physical and mechanical properties, i.e. impact toughness, hardness, and wear resistance, in comparison with steel GE 300, currently used for hammers. That ensures a longer operational cycle of the hammers steel for crushing mills. Especially appropriate was steel brand X 120Mn, which showes mechanical characteristics ensuring operational resource of at least 900 h. Figure 2 presents relative comparative wear resistance of the steels. This is one dimension that shows how much there is an increase or decrease of wear resistance of the tested sample in comparison with the wear resistance of the sample, approved as standard. The impact toughness of the tested steels is presented in Figure 3.

2.2. Preventive or restorative overlay welding

2.2.1. Technological backgrounds

The worn-out parts have a high residual resource and are preserved for a certain amount of labor and energy. In comparison with the processes of extraction and processing of materials the relative processes have low cost and insignificant energy and material consumption. As a result it is advisable to restore the worn-out parts to a wide scale. Thus providing a significant economic and environmental impact. The number of technological operations in overlay welding is 5 to 8 times less than those for the manufacturing of new parts. The capital investments for recovery of parts are 5−10 times lower than those for production of new parts. The cost of energy and materials is 10 to 20 times and 20 to 100 times lower, respectively. The price of the recovered parts are 2 to 20 times lower in comparison with newly made ones. That is especially valid for such economy branches, as energy, coal mining, extraction of ores and other mineral resources, military armor vehicles, construction of building, transport, etc. That is machines, assemblies and parts with increased requirements for hardness and wear resistance, for example caterpillar tracks, baskets and tools for earthmoving machines, conveyors, various types of mills and mixers, etc.

The relative share of recovered parts in the overall consumption of spare parts in our country does not exceed 5−8%, while in Russia, in Czech Republic, in Germany it is 3, 4, 6 times larger, respectively.

On the other hand, overlay welding may be applied also on newly made parts with the purpose of improving and/or increasing properties, such as hardness, wear resistance, corrosion resistance, etc. One of the ways to solve that problem is the preliminary arc overlay welding of wear resistant layers on newly made parts or recovery of worn-out parts. Thus the costs of materials and energy may be considerably decreased, up to a few times, and hundreds of tons of harmful emissions into the atmosphere can be stopped [5].

The process of overlay welding is especially effective in the case when nanomaterials are introduced as the overlaid wear resistant layers. Nanomaterials are widely used in scientific research and in engineering practice in the last 2−3 decades. The main aim of these studies are determined by the universality of the nanomaterials and by the possibility of their application and development of new technologies and materials useful in different fields of human activity. For example, nanomaterials can be introduced by means of the coating of the electrodes in manual arc welding or through overlay welding on the processed surface. The combination of the two methods (coating of the electrodes in manual arc welding and through overlay welding on the processed surface) is also possible. The most common used in practice are nanodiamonds, carbides, nitrideds and carbonitrides of refractory metals with nanometric size [6].

2.2.2. Experiments and results

New technologies were developed by the research team at IMSTCH-BAS with participation of the authors of the current report in partnership with the company Institute of Welding Joint-stock company: original technology for coated welding wires for TIG (tungsten-inert gas) overlay welding with powders and an innovative technology of production of nanomodified electrodes for manual arc welding in which the various nanomodifiers were introduced through the coating of the electrode. At the technology for coated welding wires for TIG (tungsten-inert gas) overlay welding with powders highest wear resistance was achieved when the layer was overlaid using tubular wire nanomodified by the addition of 2% Al_2O_3 and a matrix of Astaloy CrM prealloyed iron powder. The changes of the physical and mechanical properties were probably due to both the introduced nanopowders and the introduced quantity of chromium which guarantees that the nanopowders are absorbed within the overlaid metal.

At the technology of production of nanomodified electrodes the most significant increase of the hardness (56%) after manual arc overlay welding was obtained when the nanomodifier introduced through the coating was chromium coated titanium nitride. Substantial increase of the hardness (38%) was observed when silicon carbide was used as nanomodifier. In most cases of nanomodified standard samples, an increase of their hardness in the range from 4% to 18% was observed.

Comparative study of standard samples for wear resistance was carried out according to accelerated methodology of wearing of surface due to friction to the attached abrasive. The highest wear resistance, 70% higher than that of the reference sample was observed when the surface layer was overlaid using electrodes with TiN coated with Cr (Fig. 4).

The nanomodification made through the coating of electrodes for manual arc welding shows a considerable increase of hardness and wear resistance of the overlaid layers.

The metalographic studies of nanomodified layers obtained through manual arc welding proved that:

- The microstructure of the base metal consisted of ferrite and perlite with pronounced strips of perlite.

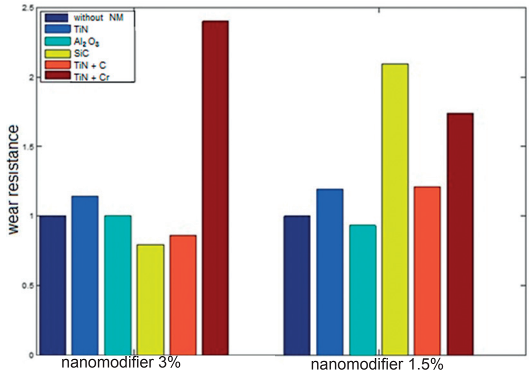
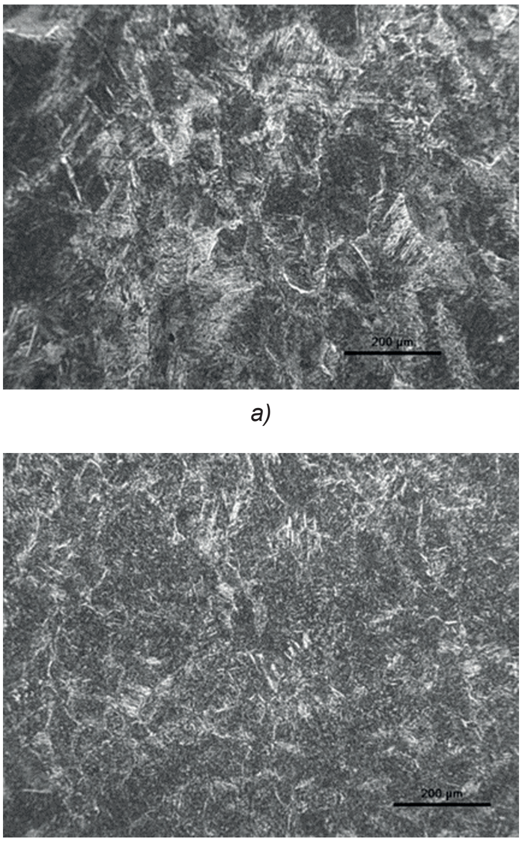


Fig. 4. Estimated wear resistance of layers overlaid with electrodes with and 3% 1.5% addition of nanomodifier (TiN, Al_2O_3, SiC, TiN + C or TiN + Cr) in the coating compared to reference electrode without nanomodifier

- The microstructure of the first layer overlaid with reference electrode IZA-E300 resembles cast structure consisting of rounded cellular bainite-martensite sections surrounded by ferrite (Fig. 5a).



a)

b)

Fig. 5. Microstructures of the overlaid layer: a) without nanomodifier, b) with nanomodifier TiN + Cr (coated with Cr)

In the microstructure of the first layer modified with TiM powder coated with Cr (TiN + Cr) bainitic and martensitic cells surrounded by ferrite was observed. This means that the modification with TiN + Cr does not result in homogenization but in significant dispersing of the microstructure (Fig. 5b). That change in microstructure had a significant influence on the increase of hardness and wear resistance of the layers nanomodified with TiN + Cr.

2.3. Thermo-chemical treatment (TCT) of parts

2.3.1. Theory

The thermo-chemical treatment is a method for combined diffusion saturation of the surface layer of the parts in gaseous, liquid or solid environment containing one or more saturating elements. TCT may be followed by quenching [7]. As the result the hardness and the wear resistance of the surface layer increases and some other specific properties are obtained, such as corrosion resistance or thermal resistance. As a rule, TCT of working tools is applied preventively to increase their hardness and wear resistance.

The types of diffusion saturation are:

A. One-component saturation, for example:

- *Carburization (saturation with carbon)*. This method is applied in low-carbon cementable steels at a temperature in the range 910°C to 930°C. Martensitic microstructure of high hardness of the surface layer is obtained after saturation and quenching at temperatures in the range 830−850°C. The treatment ends with low-temperature annealing at 180−200°C.

- *Nitriding (saturation with nitrogen)*. This method is applied on structural and tool steels alloyed mainly with chromium, molybdenum or aluminum to obtain high surface hardness and enhance corrosion and thermal resistance. Usually nitration is carried out in ammonia containing gaseous environment at temperatures in the range 500°C to 570°C during 30 to 50 hours without subsequent quenching and additional grinding due to the absence of deformation. One of the possibilities to cut down the treatment is ion nitriding. Apart from speeding, another benefit of the ion nitriding is that the treated parts that serve as a cathode in the electric circuit are heated by the glow discharge itself, which makes the external heating unnecessary.

- *Boriding*. This method is characterized in diffusion saturation of the atoms with boron in which a layer on the surface consisting of FeB and Fe_2B. The thickness of the layer reaches 0.2 mm and its hardness reaches 2000 HV. Boriding is applied to surface TCT of parts and tools which is subjected to heavy wear, such as nozzles, moulding presses and die casting moulds.

B. Multi-component saturation

As a result of the combination of different components, varieties are obtained taken to facilitate the technology and improvement of the properties. Most often the processes of nitrocarburizing and carbonitriding are applied.

- *Nitrocarburization*. The process consists mainly of saturation with nitrogen at typical for nitriding temperatures in the range from 500°C to 570°C in various gaseous environments containing ammonia and carbon compounds. In comparison with gas nitriding the process is shorter and takes 3 to 8 hours. But the achieved wear and corrosion resistance as well as thermal resistance are higher. Since the process is practically strain-free there is no necessity for quenching and grinding after saturation.

- *Carbonitriding*. This method is characterized mainly by predominantly saturation with carbon in a gaseous environment. The process has lower duration than the carburization and is carried out at temperatures in the range from 840°C to 860°C. Quenching follows after saturation. The microstructure is similar to the one after carburization but the wear resistance is higher.

Recently the so called carbide-forming powder mixtures for wear resistant coatings, e.g. Surfit 1560, find increasingly wider application. Those mixtures are used for TCT of steels containing higher concentration of strongly carbide-forming elements, as Cr, Mn, etc. During TCT at temperatures close to the melting temperature of steel various carbides are formed on the surface of the parts increasing the hardness and the wear resistance of the steel.

2.3.2. Experiments and results

Standard samples were cut out of the hammer for the crushing of lignite, shown in Figure 6, for tests as follows: tensile strength, impact toughness and wear resistance. The samples were put through thermo-chemical treatment with carbide-forming mixture. It was found that in comparison with hammers from GE 300 steel the wear resistance of treated samples was increased by 18−21%.

In this case TCT however has a number of disadvantages, for example:

- The obtained hard layer formed is very thin, very often less than 200 µm, and sometimes unable to ensure the needed resource for work.

Fig. 6. Hammer for crushing lignite

- Only relatively small parts, such as cutting tools, dies, etc. can be subjected to TCT. The larger parts require building larger furnaces, which is inconvenient and ineffective. That issue is partially solved through the invention of ion nitriding.

In IMSTCH-BAS there are developed technologies for surface strengthening of steel hammers for crushing coal. TCT is carried out by cyanation and carbide-forming powder mixtures. The results are encouraging and new research in this area is required.

3. Conclusions

The research carried out by the team indicate that the suggested technological solutions are effective and relevant to extend the life cycle of tools and machines.

The improved quality of steels through the development a complex of enhanced mechanical and physical properties, such as tensile strength, impact toughness, wear resistance, with lower production costs ensures a long-term operational resource of the item and eventually results in positive economical and environmental effects.

The conducted comparative analysis proves that the introduction of nanomodifiers through nanomodified electrodes for manual arc welding or through welding wires coated with TiN + Cr for TIG overlay welding results in a significant refinement of the microstructure and modification of the phase content of the overlaid layer. The nanomodification resulted in dispersing microstructure of the overlaid metal and increasing the hardness and wear resistance of the surface layer.

The preventive thermo-chemical treatment of small parts and tools is appropriate as the method to extend their life cycle which increased hardness and wear resistance.

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