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High-Speed Steel Technology Substitution in Mining Machinery – an Experimental Study

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Abstract

The growth of mineral extraction in countries with a developed mineral resource sector under conditions of external restrictions requires the modernization of the domestic mining machinery – an indispensable condition of which is the replacement of technologies for the production of high-speed steels and machine tools. This research was aimed at experimental studies of microstructure, phase composition and microhardness distribution in the surface layer of the R6M5 high-speed steel samples after laser cutting, cold treatment and laser tempering. It was demonstrated that after laser cutting in the surface layer of the cut there was the carbide dissolution and enrichment of the metal matrix with carbon and alloying components, resulting in an increase of residual austenite content up to 50...60 %. After the cold treatment in liquid nitrogen the content of residual austenite decreased up to 7...9 %. The laser cut surface microhardness increased up to 1000...1100 MPa. At further laser tempering the dispersion hardening processes took place, as a result the V2C carbides appeared in the steel structure amounting to 4.7 %. The microhardness increased up to 10400...10600 MPa. The study showed the possibility of using the high-speed steel laser cutting not only as a separating operation, but also as a hardening treatment. The findings contribute to the technological support for the development of domestic mining machinery in terms of replacing imported high-speed steels and machine tools.

Keywords

import substitution, mining machinery, high-speed steel, laser cutting, cold treatment, microstructure, microhardness

Introduction

The global market for equipment for surface and underground mining in 2018 was estimated at more than 15 trillion dollars with the prospect of growth by 4.5% per year to 21 trillion dollars by 2025 Key suppliers of construction and mining equipment are companies such as the Swedish Atlas Copco (turnover of $13 billion in 2020) and Sandvik ($9 billion), Japanese Komatsu Group with a turnover of $22 billion, Hitachi Construction Machinery ($6 billion in 2020), Caterpillar, USA with $42 billion (Mining World, 2024). These companies supply equipment to all the countries with a developed surface mining sector.

Along with this, in the last decade there has been an expansion of Chinese companies producing modern equipment for mines and quarries, largely due to the formation of large world-class companies in the country – SANY (turnover $10.9 billion in 2020), XCMG (operating profit $12 billion dollars in 2021), Liugong (turnover 4 billion dollars in 2022), LGMG (turnover 53 billion dollars in 2022) (Goldstein Research, 2024).

In a number of cases, national manufacturers of mining equipment face the problem of production increasing, for example, in a situation of sanctions restrictions on some supplies from abroad. In this case, a dilemma arises about the economic and production efficiency of substituting imports with domestic production, and reorienting to suppliers from other countries that do not support restrictions. Of course, cooperation with new large world-class manufacturers has its advantages, in particular, lower prices due to joining large-scale supplies. However, an increase in the output of national producers, as well as their development of new types of equipment, is more preferable, since it allows them to reduce the costs of mining, not to mention new jobs and a technological breakthrough.

Substitution of imports of mining equipment plays a special role in countries that are consistently increasing the production of traditional fossil raw materials, such as coal – in India, Indonesia, Russia (Fig. 1).

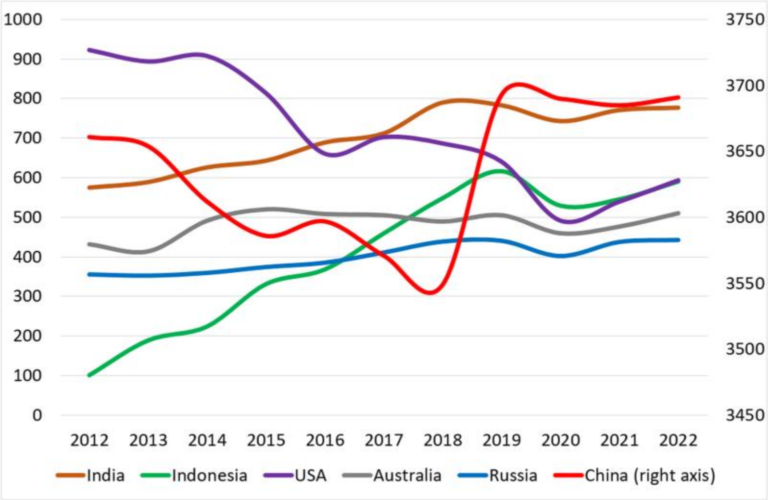


Fig. 1. Dynamics of coal production in the Top 6 countries (drafted by authors using data from (Solar Empower, 2024)).

The Russian example of recent years shows the replacement of American, Japanese, and Swedish mining equipment with products from Chinese manufacturers – for example, over the last two years SANY and XCMG increased the volume of shipments of bulldozers and excavators by 10 and 3 times respectively, SDLG – by 2.5 times, LiuGong – by 6 times, Zoomlion – by 9 times. In the supply of dump trucks to the country, Chinese companies increased their share from 10 to 40%, the remaining 40% was occupied by the BelAZ company, also increasing its share by 1.5 times (about 900 dump trucks with a total value of more than $0.8 billion) (Rastyannikova, 2022).

In turn, the replacement of imported mining equipment with domestic in Russia is happening at a slower pace, taking into account the dominance of imports in a number of segments in 2020 (Fig. 2).

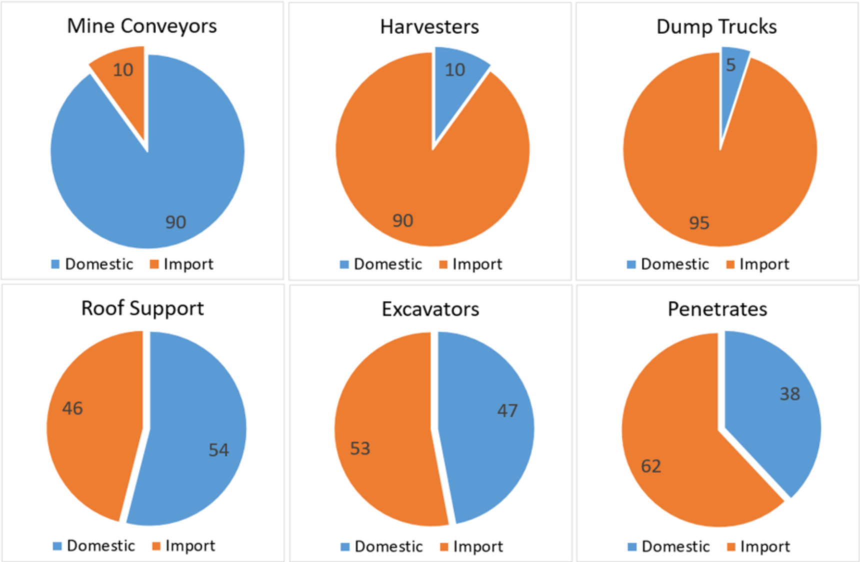


Fig. 2. Mining machinery consumption in Russia in 2020 (drafted by authors using data from (Ministry of Industry and Trade of the Russian Federation, 2023)).

From Fig. 2 follows the predominance of imports in such segments of the Russian mining equipment market as penetrators, harvesters, dump tracks and excavators – the most important and high-performance machines. At the same time, the success of replacing imported mining equipment in Russia is associated with an increase in the workload of existing enterprises, which made it possible to increase the share of domestic manufacturers in the domestic market by 7-25% by 2023 (Special Equipment and Transport, 2023).

However, breakthrough growth in the replacement of imported machinery and equipment with domestic ones is possible only if machine-building enterprises are saturated with new equipment, which also requires technologies substitution. In particular, the modernization of machine tool industry requires the development of already existing advanced technologies for the new grades of high-speed steel production, within the framework of progressive collaboration. At the same time, the Russian example shows a limiting factor for the development of machine tool industry – the lack of high-quality steels of domestic production, especially stainless and high-speed steel (in 2022, imports of the latter exceeded $1.1 billion) (Discovery Research Group, 2023). In turn, the development of the production of high-quality steels, especially for the needs of machine tool building, is impossible without increasing experimental research in the field of laser cutting as a separating and strengthening treatment of high-speed steel (Šafář et al., 2023), which is directly related to the goal of creating a competitive machine tool industry.

The future of materials processing is associated with the development of tools and technologies that ensure speed, accuracy and flexibility of production in “smart factories” controlled by cyber-physical systems at the Industry 4.0 level (Hu, 2022; Abu-Abed, 2022), which production chains with lasers fully correspond to (Waqar et al., 2023). The laser cutting technology combines the high parameters of process productivity, accuracy and quality of the cutting surface. This technology provides the ability to separate practically any metals and alloys, no matter what their thermophysical properties are. It is used in various industries, including automobile, aerospace, and medical areas (Mezzi et al., 2023; Salhi et al., 2023). In general, issues of materials laser cutting have become the subject of a wide range of research.

Research in the field of laser cutting is associated with the study of such phenomena as: the influence of boundary layer separation, shock waves, choking, etc. on interactions between the assist gas and the workpiece, including for new high-brightness laser sources (Riveiro et al., 2019); difference in cutting mechanics mild and stainless steel (Powell, 1993); the use of laser technology in “adaptive control” systems or “smart” machines (Steen, 2003); calibration of laser parameters for cutting steel materials in manufacturing industries (Naresh, 2022), as well as in construction industry – in fabrication of tubular structures (Kanyilmaz, 2019).

High power fiber laser for underwater cutting is also an object of research by a number of authors (Shin et al., 2020), as well as CO2 laser cutting for precision manufacturing of micro components for mechanical engineering and radio electronics (Parthiban et al., 2019). Striation-free laser cutting of mild steel sheets requires research of precise definition of critical cutting speed, and evaluation of the cut quality according to parameters such as kerf geometry, surface roughness and cut edge quality, is given in studies of application parameters of CO_2 laser – cutting speed, material type, workpiece thickness and assistant gas pressure (Li et al, 2007). Surface roughness is a special parameter for material processing quality, including laser cutting (Sutyagin et al., 2015; Sutyagin et al., 2016). Along with laser cutting of steels of various grades under different conditions, it is worth highlighting the research of low-damage gas-assisted laser processing of carbon fiber reinforced plastics, considering the influence of gas pressure, scanning speed and laser peak power on the cutting depth, and the width of the slit (Adamcík et al., 2023).

Materials and methods

Researchers' attention is also paid to the effects of laser heating control for increasing the efficiency of laser cutting, during the simulation of the cutting process based on such parameters of laser beam diameter function, as element thickness, cutting speed and laser power (Shamlooei, 2022). In turn, it is proposed to study the possibility of reducing surface roughness in laser cutting taking into account such operating parameters as pulse width, frequency and the interaction of frequency and pulse width (Buj-Corral, 2021).

Issues of laser cutting of various types of steels under various conditions dominate in research in this area. A significant amount of experience has been acquired and the technological recommendations have been developed enabling to separate carbon, low-alloyed steels and some non-ferrous metal alloys with high productivity and quality. The issues of technological quality of the laser cutting process and the place of this technology in the preparation of products have not been sufficiently developed for the high-alloy steels and compositions based on them (Izmailov et al., 2021; Afanasieva, Izmailov et al., 2021; Afanasieva, Barabonova et al., 2021).

It is well known that structural transformations occur in the cutting zone under the thermal influence of laser radiation, resulting in changes in the structure and mechanical properties of the material. The laser treatment zone has a layered structure due to the fact that different metal layers are heated to different temperatures. There are three principally different phase transformation layers: melted metal (the liquid phase quenching zone), metal that has been subjected to structural and phase changes (the solid phase quenching zone), and the layer of transition to the base that remains unchanged (the tempering zone) (Izmailov et al., 2021; Afanasieva, Izmailov et al., 2021).

Although the high-speed steels are inferior to hard alloys in heat resistance and hardness, they still remain widely used for manufacturing tools, especially of complicated shapes and large sizes, due to their higher strength and toughness and much better technological properties. The tool resistance of the high-speed steel tools may be higher than that of carbide tools when cutting some ductile and difficult-to-machine materials such as austenitic steels, titanium alloys and some others (Geller, 1975).

It is possible to rationalize the use of expensive high-alloy high-speed steels by improving the existing tool designs, technologies of their production, as well as increasing the operability of tool steel. The standard hardening treatment for tools is the high temperature quenching, which leaves more than 30% of residual austenite in the steel structure. The cold treatment and once high-temperature tempering or three-fold tempering at 560 °C are performed immediately after quenching to eliminate the residual austenite, as well as the dispersion hardening processes (Geller, 1975). The repeated tempering process depletes the martensite by carbon and alloying components, which leads to unstrengthening of the martensite. The high-speed steels are the most complex iron-based alloys. The conventional methods of hardening tools made of the high-speed steels do not fully reveal their potential capabilities (Adaskin et al., 2011; Kremnev, 2008; Kremnev et al., 2012). Due to the continuous improvement of operating conditions, the necessity to develop new methods of manufacturing and hardening of tools with an increased level of properties becomes acute.

Therefore, it is necessary to study the influence of cold treatment and laser tempering on the structural phase state of the high-speed steels after laser cutting.

The research in the field of the influence of laser cutting and treatment on microstructure and mechanical properties of high-speed steel is quite extensive and is based on many grades of steel (Cunha et al., 2022; Voropaev et al., 2022). So, for the experimental studies we used the R6M5 high-speed steel, which is the leading steel in the tool manufacturing market in the world. It refers to the tungsten-molybdenum steels of the optimal composition. The average content of carbon and alloying components in steel according to National State Standard 19265-73 is given in Table 1.

The R6M5 steel pieces of 120×40×3.3 mm in size were pre-hardened by the volume hardening and three times tempering at 560 °C, and then they were cut on the technological laser complex with nitrogen blowing on the regimes that ensure the roughness of the cut surface (arithmetic mean deviation of profile) $R_a = 1,2 \pm 0,05$ µm (Table 2).

Table 1. Chemical composition of the high-speed steels, % wt

C	Si	Mn	Ni	S	P	Cr	Mo	W	V	Co	Cu	Fe
0.82–0.9	0.2–0.5	0.2–0.5	up to 0.6	up to 0.025	up to 0.03	3.8–4.4	4.8–5.3	5.5–6.5	1.7–2.1	up to 0.5	up to 0.25	bal

Table 2. Technological modes of laser cutting

Sample thickness, mm	Radiation power, W	Cutting speed, m/min	Gas (nitrogen) pressure, MPa
3.3	1800	0.017	0.9

The laser tempering was performed after the cold treatment to increase the heat resistance of steel in the laser treatment zone. The same phase and structural transformations occur during the rapid tempering of hardened steel as occur during the slow heating in the furnace. It is possible to temper at the heating temperature up to the point A_{c1}, where the austenite structure is formed, since the laser treatment is short-lasting. For the R6M5 steel this temperature is equal to 820° C.

The equipment consists of a multi-channel CO_2 laser specially designed for surfacing and thermal hardening with an output radiation power of 3 kW, and a technological station with five coordinates for beam manipulation and two coordinates for manipulating the workpiece, providing wide technological capabilities for processing any complex surfaces of parts.

The microstructure studies were carried out with the help of optical metallographic microscope Carl Zeiss Axio Vert.A1MAT and scanning electron microscope JEOL JSM 6610LV.

The microhardness $HV_{0,2}$, MPa, was measured by means of PMT-3 device according to National State Standard R 8.748-2011 (ISO 14577-1:2002). The phase composition of steels was analyzed by the X-ray diffractometer DRON-4-07 with use of monochromatized cobalt K_{α}-radiation.

Results

The Structural Phase State of the High-Speed Steels after Laser Cutting

The surface of a laser cut is characterized by microgeometry, which appears to be a set of periodically repeating irregularities: waviness, grooves, roughness. Despite the large number of theoretical and experimental works devoted to the formation of the cut surface, the nature of the formation of irregularities has not yet been fully studied due to the complexity and multifactorial nature of the cutting process.

In particular, grooves can arise due to the hydrodynamic instability of the melt layer, caused by the forceful effect of the gas jet on the melt. An analysis was carried out (Li et al., 2007), and for low-carbon steel, the critical cutting speed at which grooves are minimized was experimentally found. The highest surface quality is achieved in the stationary laser cutting mode, when the liquid melt pool is located along the entire length of the cutting channel, and the rates of metal melting in the cutting direction and removal of molten metal in each section of the channel are equal. At lower laser cutting speeds, a non-stationary mode occurs, characterized by the periodic ejection of molten metal from the processing zone, while the quality of the cut surface significantly deteriorates.

Fig. 3 shows images of the laser-cut surface of high-speed steel at various magnifications, obtained using scanning electron microscopy. It can be seen that, along with macroscopic grooves, the cut surface at the micro level is represented by a drop-shaped structure, characteristic of surfaces formed during free crystallization. Dendrites grow in the form of spherulites.

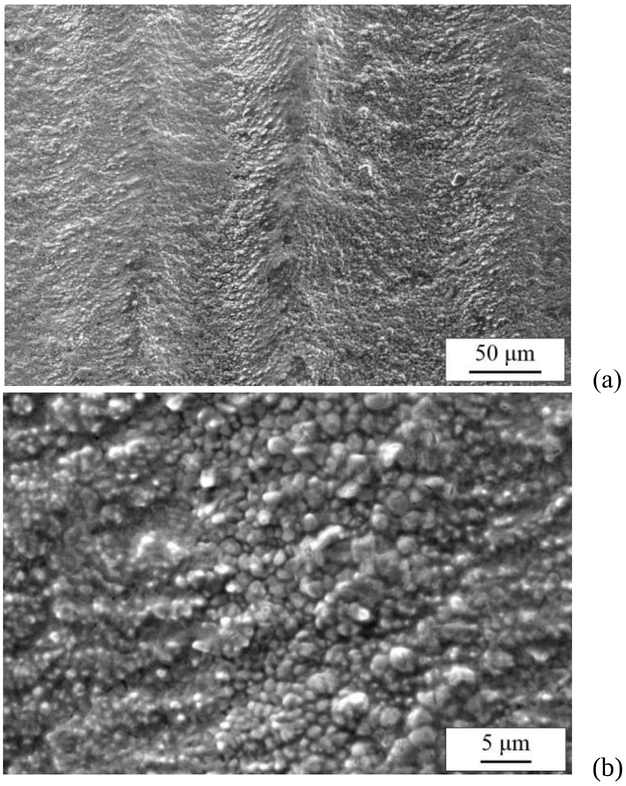


Fig. 3. Image of the laser cut surface of high speed steel (a) and (b) different magnifications

The thermal influence zone is created during the laser cutting, where the high-speed hardening of the cut surface layers takes place. Fig. 4 shows an image of the microstructure of the R6M5 high-speed steel, cross section.

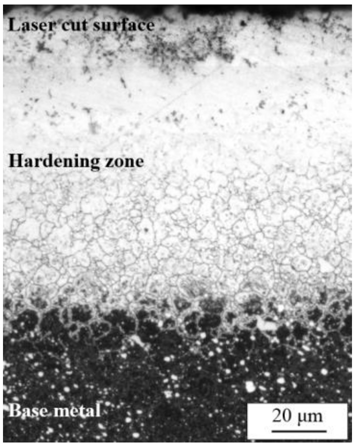
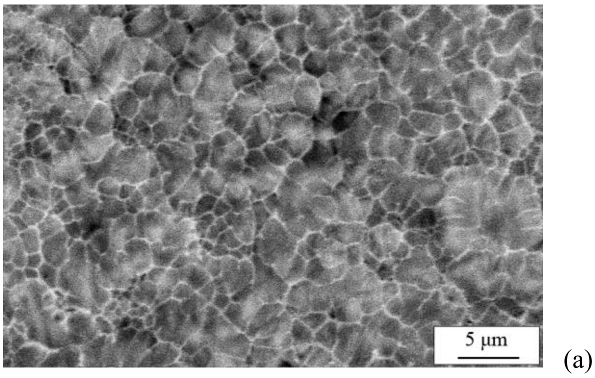


Fig. 4. Microstructure of steel in the heat-affected zone. Optical image.

The hardening zone appears as a light band with a width of about 120 µm. The lower border of this layer is specified by heating of steel up to the critical temperature A_{c1}. The matrix re-hardening occurred in this zone, the structure of this zone is heterogeneous and it is possible to distinguish two parts. The surface layer with depth up to 40 µm is a zone of quenching from the liquid phase, i.e. the high-speed recrystallization of steel occurred here, most of the carbides dissolved in the metal matrix, and enriched the austenite and martensite solid solutions with carbon and alloying components. The heating temperature in this zone was higher than the melting temperature. The steel microstructure in this zone is shown in Fig. 5a. The steel has a cellular structure with an average cell size of 2-3 µm. Eutectic carbides in the form of thin interlayers appear along the cell boundaries. The steel microhardness in this zone is about 8900 MPa.

The second part of the quenching zone with a length of about 70...80 µm was formed when the steel was heated up from the melting temperature to the point A_{c1}. The metal matrix from the solid phase was re-hardened in this zone, the large primary carbides were dissolved incompletely (Fig. 5b). Comparison of the microstructure of this zone with the base metal (Fig. 5c) shows a noticeable reduction in the amount of carbides The steel microhardness in this zone is slightly higher and is equal to 9100 MPa.

The transition zone (or tempering zone) is generated when the steel is heated below the point A_{c1} in the temperature range of 820-620 °C. The lower border of this interval corresponds to the value of steel heat resistance. The hardness may decrease in this zone due to martensite decomposition. The degree of de-hardening depends on the laser cutting modes as well as the steel structural state. The shorter the duration of thermal influence, the higher is the steel hardness in the transition zone. For the studied samples the decrease of steel microhardness in the transition zone was not revealed, the microhardness values are the same as for the base metal, about 8300 MPa. This is probably connected with the fact that the samples before laser cutting were hardened by hardening and triple tempering, the steel had sufficient heat resistance and the short-term heating in this temperature range did not result in martensite decomposition.



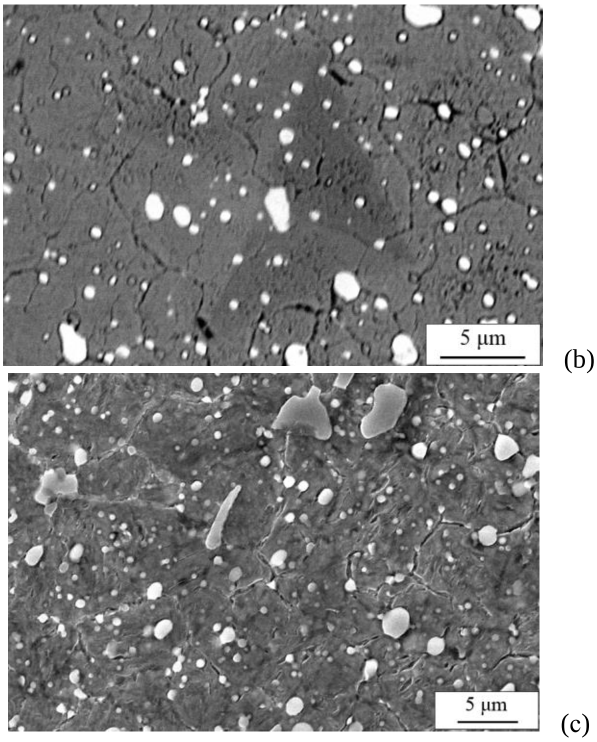


Fig. 5. (a) SEM image of the laser cut surface of steel; (b) microstructure after hardening from the solid phase; microstructure after hardening and triple tempering (c).

The paper (Adaskin et al., 2011) studied the nature and causes of fracture of the high-speed steels. Since there is hardly any ductile structural component in the fracture of quenched and tempered high-speed steels of the Ledeburite class, their hardness is essentially characterized by resistance to brittle fracture. It has been experimentally established that the crack formation is most likely to occur at the carbide-matrix border. A defect zone is created around the carbide, the size of defect zone depends on the size of the carbide. As the high-speed steels made by standard technology contain the large eutectic carbides in their structure (Fig. 5c), the early failure of a tool is often due to the crumbling of large carbides in the tool cutting edge.

The results of metallographic analysis revealed a significant decrease in the number of primary carbides in the hardening zone microstructure, especially in the liquid phase hardening zone. This means that if the tool's working surface is formed by laser cutting, the premature failure of such a tool due to the spalling of large carbides is excluded, since they are absent in the tool's cutting edge.

Table 3 presents the results of X-ray phase analysis of high-speed steel in the hardening zone, where 2θ is the scattering angle in relation to the beam axis and *d* indicates the interplanar distances. The phase composition of steel is represented by martensite, about 3...8% of undissolved carbides Fe_3W_3C. The amount of residual austenite in the hardening zone after laser cutting totaled about 50 ... 60 %. The increased amount of residual austenite is unacceptable, and it is necessary to search for solutions to reduce its content.

Table 3. The results of X-ray phase analysis of steel in the hardening zone after laser cutting.

No	2θ, ˚	d, Å	Phase	HKL
1	41.34	2.5358	Fe_3W_3C	331
2	47.52	2.2216	Fe_3W_3C	422
3	50.62	2.0937	γ	111
4	51.82	2.0485	α'	110
5	58.84	1.8223	γ	200
6	88.08	1.2876	γ	220
7	98.44	1.1821	α'	211
8	108.40	1.1036	γ	311
9	117.34	1.0534	γ	222

Cold Treatment

The residual austenite in high-speed steels is very stable due to high alloy content and is transformed into martensite only after tempering under temperatures above 500 °C (Geller, 1975). In addition to tempering, the cold treatment is an effective way to eliminate residual austenite. It is a continuation of hardening and resumes the martensitic transformation of residual austenite, which is considered within complementary research of deep cryogenically treated steels (Jovičević-Klug et al., 2021), analysis of the effect of sub-zero treatment on the hardness, fractography and other properties of nickel and steel alloy (Liao et al., 2020), analysis of the influence of deep cryogenic treatment on microstructure property of high-speed steel (Zhou et al., 2019), investigation of the influence of heat treatment parameters on effectiveness of deep cryogenic treatment of high-speed steels (Jovičević-Klug et al., 2022), study of deep cryogenic time prolonging (Xu et al., 2022).

According to the data of X-ray phase analysis (Table 4) the amount of residual austenite in the hardening zone of high-speed steel decreases up to 7-9 % after the cold treatment in liquid nitrogen. The hardness increases significantly (Table 5).

Table 4. The results of X-Ray phase analysis of steel in the hardening zone after laser cutting and cold treatment.

No	2θ, °	*d*, Å	Phase	HKL
1	*41.40*	*2.5323*	Fe_3W_3C	*331*
2	*46.92*	*2.2484*	Fe_3W_3C	*422*
3	*49.86*	*2.1236*	Fe_3W_3C	*511*
4			γ	*111*
	51.82	*2.0485*	α'	*110*
5	*59.44*	*1.8055*	γ	*200*
6	*76.92*	*1.4391*	α'	*200*
7	*98.44*	*1.1823*	α'	*211*

Table 5. Values of $HV_{0,2}$ microhardness, MPa of the R6M5 high-speed steel in the thermal influence zone after laser cutting, cold treatment and laser tempering.

Measuring Area	Processing		
	Laser Cutting	Cold Treatment	Laser Tempering
Liquid Phase Hardening Zone	8900 ± 130	10000 ± 120	10400 ± 130
Solid Phase Hardening Zone	9100 ± 110	10100 ± 120	10600 ± 120
Tempering Zone	8300 ± 120	8300 ± 130	8300 ± 130
Base Metal	8300 ± 130	8310 ± 140	8310 ± 145

One of the drawbacks of cold treatment is the increase of steel volume due to the fact that the crystal lattice period of α-iron is larger in comparison with γ-iron. The difference in lattice period values results in the appearance of additional structural and thermal stresses and the crack formation. Even at cryogenic temperatures, the martensitic transformation does not occur completely due to large internal stresses in the metal, and a certain amount of retained austenite remains in the steel composition.

Since at laser cutting of steel the hardening zone has a depth of about 120 µm, the martensitic transformation will be intensive only in the thin hardened layer. Since the base metal has a lower hardness than the hardened layer (Table 5), it is possible that the formed stresses will be relaxed.

The cold treatment after laser cutting of the high-speed steel has an advantage, because the elimination of residual austenite takes place without de-hardening of martensite. A high amount of dissolved carbon and a high degree of martensite alloying are preserved.

Laser Tempering

The main property of the high-speed steel is its high thermal resistance. Steel acquires this quality due to dispersion hardening during repeated tempering under the temperature of 540...560 ºC (Adaskin et al., 2011). It is proposed to apply laser tempering for this purpose, because dispersion hardening should take place only in the surface layer, i.e. in the hardening zone.

It is necessary to select those modes of laser tempering that will allow dispersion hardening processes to take place in the hardening zone, and the transition zone will not be de-hardened. It is necessary to know the depth of the hardening zone and to select the laser tempering modes depending on it in order to solve this problem.

The hardness and heat resistance of the high-speed steels are higher than the greater the number of dispersed carbides released from martensite during tempering and the greater their resistance against coagulation when heated above the tempering temperature (Karmakar et al., 2019; Amirabdollahian et al., 2021). The type and properties of the released carbides depend on the ratio (K) of alloying components and carbon in the martensite. K = ∑(W, Mo, V), % at / C, % at [22]. When K = 2, the most stable M_2C carbides based on tungsten and molybdenum are isolated from the martensite. Substitution of tungsten and molybdenum atoms for vanadium atoms in the crystal lattice of M_2C carbide increases the stability of these carbides against coagulation. This is explained by the fact that vanadium is a stronger carbide-forming component than tungsten and molybdenum.

Fig. 6 presents X-ray diagrams of the surface layer of laser cut R6M5 steel before and after laser tempering. As can be seen from the ratio of the lines, after tempering the amount of retained austenite decreased significantly. The peaks corresponding to α-iron became more intense. This fact should have a positive effect on the properties of steel, helping to increase the hardness and dimensional stability of the tool during operation.

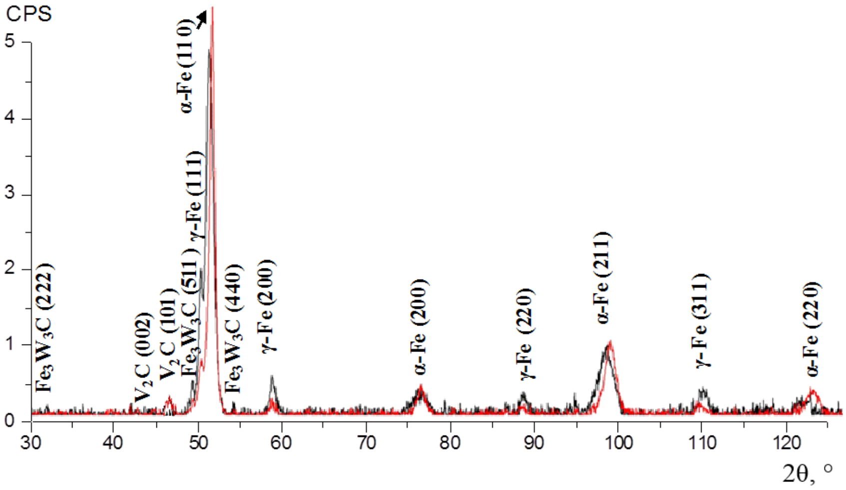


Fig. 6. Radiograph comparison of the R6M5 steel sample before laser tempering (black spectrum) and after laser tempering (red spectrum).

Fe_3W_3C carbides are present in the steel composition before and after laser tempering. Most likely, these carbides were not dissolved during laser cutting and are already present in the original workpiece. Their number is minimal in the liquid phase hardening zone and increases with distance from the cut surface.

During the tempering 4.7 % of V_2C carbides were formed. The steel microhardness in the hardening zone increased up to 10400...10600 MPa.

The performed researches have revealed the possibility of application of laser cutting of the high-speed steels simultaneously as a separating and hardening operation. The depth of the hardening zone of the cutting surface is not large, so it is preferable to perform cutting at the steady-state modes, providing the roughness parameters required for the cutting edge, so as not to use mechanical processing. For large dimensions, this condition is difficult to realize, so this technology can be used in the production of low-dimensional tools.

Discussion

Fig. 7 shows heat treatment schemes for high-speed steel. One of the traditional (standard) hardening methods is marked with blue. The option described in this article is marked with red. The non-sharpening working surface of a high-speed steel tool is formed by laser cutting, during which the surface layer is hardened. Then, to eliminate residual austenite and increase the hardness and heat resistance of steel in the hardened zone, it is proposed to perform cold treatment in liquid nitrogen and laser tempering. The heating temperatures indicated in the figure during laser cutting and laser tempering are typical only for the surface layer of steel.

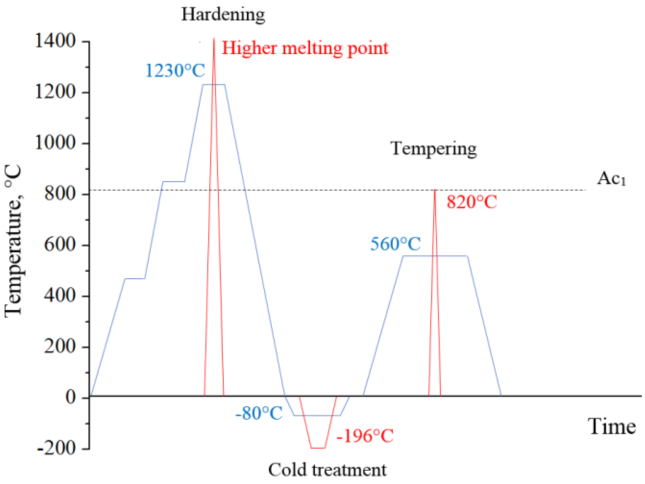


Fig. 7. Schemes for strengthening treatment of high-speed steel

Unlike standard heat treatment technology, laser cutting and tempering technologies are characterized by very high heating and cooling rates of steel and short exposure times. Thanks to higher temperature heating, it is possible to achieve a similar result comparable to standard processing (Razumov et al., 2009).

The study of the influence of cold treatment and laser tempering on the structural-phase state of the laser-cut surface of high-speed steel made it possible to identify the following patterns:

1. When laser cutting high-alloy steel, a hardened zone with a depth of about 120 microns with an increased content of retained austenite (50 – 60%) is formed. Cold treatment in liquid nitrogen can reduce the amount of retained austenite to 7 – 9%. In this case, the transition zone does not soften.
2. During laser tempering, vanadium is predominantly released from the solid solution. Dispersion hardening occurs with the formation of V_2C carbides in an amount of 4.7%. The carbide-forming elements tungsten and molybdenum are partially retained in the solid solution, delaying the decomposition of martensite.
3. Laser tempering increases the hardness of high-speed steel by 400 – 500 MPa.
4. During laser cutting, dissolution of primary carbides occurs in the metal matrix: intensive in the hardening zone from the liquid phase and partial in the hardening zone from the solid phase. For the working surfaces of tools formed using laser cutting, premature failure during operation due to chipping of large carbides is excluded, since they will be absent from the cutting edge of the tool.

All this made it possible to advance in the study of technology for hardening high-speed cutting steels in comparison with existing works, thanks to the author's experiment. The main achievement of this research can be considered the experimentally confirmed possibility of using laser cutting not only as a separation, but also as a hardening treatment, which can be the basis for the development of new methods for manufacturing tools.

In accordance with the author's hypothesis, the transition to new technologies for processing tool steel makes it possible to gradually expand the capabilities of the domestic mechanical engineering industry to produce new machines, without which it is impossible to replace imports of mining equipment.

Conclusions

Since the substitution of tool steel processing technologies is the first step towards replacing the import of materials for the domestic machine tool industry, the development of the production of mining equipment should begin with the intensification of fundamental research in the field of metalworking. In this regard, the research of technologies of the influence of laser cutting, cold treatment in liquid nitrogen and subsequent laser tempering on the structural-phase state and microhardness of the R6M5 high-speed steel, widely used in the production of metal-cutting tools, is of particular relevance. The laser cutting process forms a thermal influence zone in the surface layers of the cut, consisting of a liquid phase hardening zone up to 40 μm deep with a microhardness of 8900 MPa and a solid phase hardening zone up to 70...80 μm long with a microhardness of 9100 MPa. The content of residual austenite in the hardening zone is equal to 50...60 %. The transition zone (tempering zone) has the same microhardness with the base metal equal to 8300 MPa. The steel was subjected to cold treatment in liquid nitrogen and laser tempering immediately after laser cutting to eliminate residual austenite and harden the hardening zone by means of dispersion hardening. According to the data of X-ray phase analysis the amount of residual austenite after cold treatment in the hardening zone decreases up to 7...9 %. This results in an increase in microhardness up to 10100 MPa. The laser tempering produced 4.7 % of V_2C carbides. The steel microhardness in the hardening zone increased up to 10400...10600 MPa. The carried-out researches have demonstrated the possibility of application of laser cutting for high-speed steels simultaneously as separating and hardening treatment. It is recommended to use this technology for production of the small-sized tools.

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