https://doi.org/10.21122/2227-1031-2019-18-5-369-379

UDC 534.2

# Improving Properties of Tool Steels by Method of Dynamic Alloying

**A. S. Kalinichenko[1], V. I. Ovchinnikov[2], S. M. Usherenko[1], Javad F. Yazdani-Cherati[1]**

[1]Belarusian National Technical University (Minsk, Republic of Belarus),
[2]The State Scientific Institution "Powder Metallurgy Institute", Separate self-supporting division "Research Institute of Pulse Processes with pilot production " (Minsk, Republic of Belarus)



**Abstract.** The influence of high-speed particle fluxes on changes in the structure and properties of materials has been widely studied currently. The effect exerted by particles moving at very high speeds can have both negative (in spacecrafts) and positive character (dynamic processing of tool steels). Therefore a task for studying an effect of high-speed particle flows on structure change in tool steels and improving their performance properties has been set in the paper. The study has used an explosive method for creation of a high-speed flow of SiC + Ni and $Al_2O_3$ particles. Samples after dynamic alloying have been subjected to diffusion nitriding. Microstructure of specimens made of X12M, R18, R6M5K5- steel has been studied using optical and electron metallography. Wear resistance of the samples has been also tested on a friction machine. Theoretical and experimental results on a complex effect of high-speed microparticle flows and nitriding on a structure and properties of tool steels have been obtained during the research. It has been established that dynamic alloying by particles leads to formation of a specific structure in a composite material reinforced with channels. Central fiber (channel) zone with powder particles residues is surrounded by areas of amorphous state which is succeeded by a zone with a nanocrystalline fragmented cellular structure. Then we observe a zone with a microcrystalline structure that transits to a zone with crystalline structure which is characteristic for a matrix material of structural steel. The obtained data can expand and complement some ideas about mechanisms for dynamic loading of solids and condensed matter, plastic deformation, physical mechanics of structurally inhomogeneous media at different levels, a number of effects arising from collision and ultra-deep penetration of microparticles into metals. It has been shown that wear resistance of high-speed steel subjected to dynamic alloying in the quenched state is increased by 1.2 times in comparison with wear resistance of steel alloyed in the annealing state.

**Keywords:** dynamic alloying, microstructure, nitriding, wear resistance

**For citation:** Kalinichenko A. S., Ovchinnikov V. I., Usherenko S. M., Yazdani-Cherati Javad F. (2019) Improving Properties of Tool Steels by Method of Dynamic Alloying. *Science and Technique*. 18 (5), 369–379. https://doi.org/10.21122/2227-1031-2019-18-5-369-379

# Повышение свойств инструментальных сталей методом динамического легирования

**Докт. техн. наук А. С. Калиниченко[1], канд. техн. наук В. И. Овчинников[2], докт. техн. наук, проф. С. М. Ушеренко[1], асп. Джавад Ф. Яздани-Черати[1]**

[1]Белорусский национальный технический университет (Минск, Республика Беларусь),
[2]Государственное научное учреждение «Институт порошковой металлургии», Обособленное хозрасчетное структурное подразделение «Научно-исследовательский институт импульсных процессов с опытным производством» (Минск, Республика Беларусь)

**Реферат.** В настоящее время достаточно широко изучаются вопросы влияния высокоскоростных потоков частиц на изменение структуры и свойств материалов. Эффект, который оказывают частицы, двигающиеся с очень высокой скоростью, может быть как негативный, например в космических аппаратах, так и положительный – при динамической

**Адрес для переписки**
Калиниченко Александр Сергеевич
Белорусский национальный технический университет
просп. Независимости, 65,
220013, г. Минск, Республика Беларусь
Тел.: +375 29 190-64-90
akalinichenko@bntu.by

**Address for correspondence**
Kalinichenko Alexander S.
Belarusian National Technical University
65 Nezavisimosty Ave.,
220013, Minsk, Republic of Belarus
Tel.: +375 29 190-64-90
akalinichenko@bntu.by

обработке инструментальных сталей. Поэтому была поставлена задача исследования воздействия высокоскоростных потоков частиц на изменение структуры инструментальных сталей и повышение их эксплуатационных свойств. В работе использовался взрывной метод создания высокоскоростного потока частиц SiC + Ni и $Al_2O_3$. Образцы после динамического легирования подвергались диффузионному азотированию. Микроструктура образцов из сталей Х12М, Р18, Р6М5К5 изучалась с помощью оптической и электронной металлографии. Испытывалась и износостойкость образцов на машине трения. В ходе исследований получены теоретические и экспериментальные результаты по комплексному воздействию высокоскоростных потоков микрочастиц и азотирования на структуру и свойства инструментальных сталей. Установлено, что динамическое легирование частицами приводит к формированию специфической структуры композиционного материала, армированного каналами. Центральная волоконная (канальная) зона с остатками частиц порошка окружена областями с аморфным строением, она сменяется зоной с нанокристаллической фрагментированной ячеистой структурой. Затем наблюдается зона с микрокристаллической структурой, которая переходит в зону кристаллического строения, характерного для матричного материала конструкционной стали. Полученные данные могут расширить и дополнить некоторые представления о механизмах динамического нагружения твердых тел и конденсированных сред, пластической деформации, физической механики структурно-неоднородных сред на различных уровнях, о ряде эффектов, возникающих при соударении и сверхглубоком проникании микрочастиц в металлы. Установлено, что износостойкость быстрорежущей стали, подвергнутой динамическому легированию в закаленном состоянии, увеличивается в 1,2 раза по сравнению с износостойкостью стали, легированной в состоянии отжига.

**Ключевые слова:** динамическое легирование, микроструктура, азотирование, износостойкость

**Для цитирования:** Повышение свойств инструментальных сталей методом динамического легирования / А. С. Калиниченко [и др.] // *Наука и техника*. 2019. Т. 18, № 5. С. 369–379. https://doi.org/10.21122/2227-1031-2019-18-5-369-379

## Introduction

Currently, the influence of high-speed particle flows on changes in the structure and properties of materials is widely studied. It is established that high-speed flows of dust particles due to the effect of super-deep penetration can cause failure of electronic devices at space stations. As a result, some special measures must be developed for protection of electronic units in space environment [1, 2].

One of the promising directions and methods of materials processing are high-energy pulse methods that provide dynamic restructuring of the structure and properties. At present, extensive scientific, theoretical and experimental data on the investigations of physical and mechanical properties of metals surface layers under pulsed loading are obtained. Much less results were published on the study of deep layers in condensed matters [3–5].

So far, the basic peculiarities of high-speed deformation of metals and changes in their properties in the zone of the shock wave penetration have been established [6]. But the mechanism of interaction of high-energy flows of powder particles with the matrix is not fully explained. There is practically no explanation for the formation of electromagnetic radiation and magnetic fields, the formation of which is fixed, as well as their effect on thermodynamic, chemical and electrical properties, structural and energy changes in condensed media.

Improving the operational stability of machine parts and mechanisms, tools are inextricably linked to the increase in the physical and mechanical characteristics of the metal (wear resistance, toughness, bending strength), as many parts, including cutters for mining machines, operate in conditions of abrasive wear, sudden temperature changes and shock loads. The complex solution of questions dealing with the increase in durability of products is an important problem for machine-building branch in general and mining one in particular.

Increasing the wear resistance of working bodies' parts and tools is mainly achieved by alloying and deposition of wear-resistant protective coatings, chemical and thermal treatment, as well as the use of special materials.

A significant disadvantage of traditional hardening methods is that the increase in wear resistance is usually accompanied by a decrease in bending strength and toughness. In addition, scarce and expensive elements (tungsten, cobalt, molybdenum, etc.) are used for alloying and hardening.

Therefore, non-traditional technologies of metals and tools hardening are of interest. One of these methods is the use of explosive hardening of parts, including tools for the mining industry including the production of potassium salts. Earlier studies have been implemented dealing with the development of hardening technology of tool steel by the method of dynamic alloying with the application of the explosion energy to accelerate the flow of the alloying substances [7, 8].

The study of the processes accompanying the interaction of the high-speed particles flow with a metal matrix contributes to the understanding of the dynamics of changes in the state of matter. Modes of dynamic action of the particle flow provide a change in the physical and mechanical properties of metals and non-metals, as well as the evolution of their structure [9, 10]. Features of particle penetration contribute to the formation of composite materials with an increased level of properties that is important for practical applications.

The main features of the technology of materials explosion treatment with high-speed flows of powder particles include: high concentration of energy introduced into the impact zone, locality and precision processing at significantly lower total energy consumption. Due to this, it is possible to reduce and combine certain types of processing, as well as to ensure a controlled process of forming the structure of materials. The use of cumulation of energy flows and powder particles allows solving one of the problems of obtaining composite materials, including structured ones and materials with new properties.

This work is devoted to the study of the processes of microstructure and properties formation in specimens, as well as the mechanism of the base material hardening due to complex processing of tool steels during the dynamic alloying of the metal matrix by powder particles and nitriding.

## Materials and methods of research

The experiments were carried out on cylindrical samples with a diameter of 8 mm made of steel X12M, R18, R6M5K5 and processed by a high-speed flow of particles SiC + Ni and $Al_2O_3$ of fraction 50–100 μm. The background pressure was about 2 GPa, the exposure time was about 40 μs. Steel specimens after pulsed exposure to the powder particles flow were cut from the processing side to a depth of 1 mm. After that, the specimens were subjected to diffusion nitriding for 1 hour. The wear resistance of steel alloyed with SiC powder was evaluated by determining the wear rate of the samples in the machine AI-1 during the friction with the grinding wheel (GOST 2424–83). The specific pressure was maintained at 0.6 kg/cm$^2$. The speed of the circle rotation was 330 min$^{-1}$. Explosive matter "Ammonite 6ZV" was used in amount of 200 g. The microstructure of the samples before and after treatment was investigated using the microscope "Metam-21", electronic microscope "Stereoscan-360". Phase analysis of the samples was performed on the X-ray diffractometer DRON-3 in Fek$_\alpha$ monochromatized radiation.

## Results and discussion

*Optimization of the scheme and modes of dynamic alloying of hardened tool steel.* The fact that the impact and penetration of particles is inextricably linked to the loading of the barrier (sample) with dense high-speed particle flow, an important aspect is the optimization of the process and the correct choice of processing method. This feature causes necessitates of more detailed study of the structure of the particle flow formed by the explosive accelerator. Scheme of accelerator is depicted in fig. 1. It is necessary to establish the relations between the flow parameters and peculiarities of the particles penetration into the processed sample, as well as the degree of their influence on overall process. These parameters are an important condition for process control and ensuring required properties of the product.

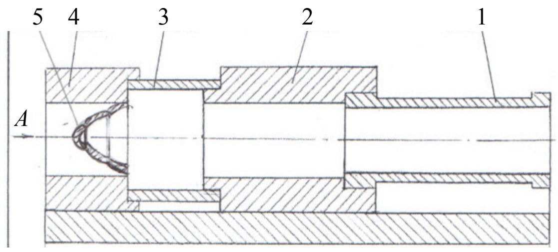


*Fig. 1.* Scheme of microparticles accelerator design:
1 – guide of the particles flow with the desired diameter;
2 – adjusting (focusing) support; 3 – chamber of the of particles flow formation; 4 – body of the explosive device;
5 – cumulative funnel (lens)

The simplest means of controlling the flow parameters are the change of technological features of the accelerator, including the choice of the optimal geometric configuration of the accelerator for specific technical purposes, the design of its elements, the quantity and quality of the explosives used for this purpose. The main elements of the accelerator are the powder container and the adjusting support. The adjusting support is a thick-walled steel pipe and is used to set a predetermined distance from the powder container to the workpiece, as well as to focus the powder jet formed during the compression of the container with the powder by charge of the explosive. Fig. 2a shows a scheme of steel R6M5 treatment.

The shape of the container affects the speed of the jet and the uniformity of the powder particles distribution along its flow. Containers made of aluminum sheet 1.5 mm thick with the shape of a hemisphere, a hollow cylinder or three docked hemispheres of different diameters were used (fig. 2b). Non-uniformity of surface treatment of alloyed specimens was observed after using a container in the shape of a hemisphere. It was found for this case that zones of significant plastic deformation were observed along with shallow micro-craters (0.5–1.0 mm) which evenly distributed on the surface. The depth and diameter of plastic deformation zones reach 8–10 and 15–18 mm, respectively.

The presence of such heterogeneous in the degree of plastic deformation zones leads to stresses that adversely affect the properties of the product and contribute to the process of cracking during subsequent heat treatment.

The container in the form of three docked hemispheres of different diameters allows increasing the uniformity of processing. The maximum velocity of the powder particles jet can be obtained using a container in the form of a hollow cylinder, which follows from the basic ratio of the cumulation theory

$$\omega_1 = \frac{\omega_0}{\operatorname{tg}\frac{\alpha}{2}},$$

where $\omega_1$ – velocity of the jet, m/s; $\omega_0$ – rate of collapse of the cladding elements, m/s; $\alpha$ – angle of collapse, deg.

The containers with the powder composition in the form of a cylinder with an inner diameter of 25 mm were used in experiments conducted. The higher particles speed (in the case for a container of cylindrical shape) contributes to the increase in the depth of their penetration into the material, but also increases the danger of crack formation and destruction of parts. Therefore, to obtain high-quality products, it is necessary to increase the distance between the explosive accelerator and parts made of quenched high-speed steel in comparison with the distance that provided high-quality hardening of the same steels parts in the annealed state. High hardness (61~66 HRC) of quenched high-speed steels dramatically increases the risk of cracking during dynamic alloying, which makes it necessary to study the structural state of the steel after quenching.

In high-speed steel parts the $\alpha \rightarrow \gamma$ transformation and dissolution of some excess carbides in the resulting austenite occur during the process of heating for quenching. After quenching in the structure of steel part of austenite (residual) and excess carbides, as well as martensite, retained. During the explosive alloying of quenched steels a volume network of microchannels forms in their structure, and the processes of residual austenite peening take place.

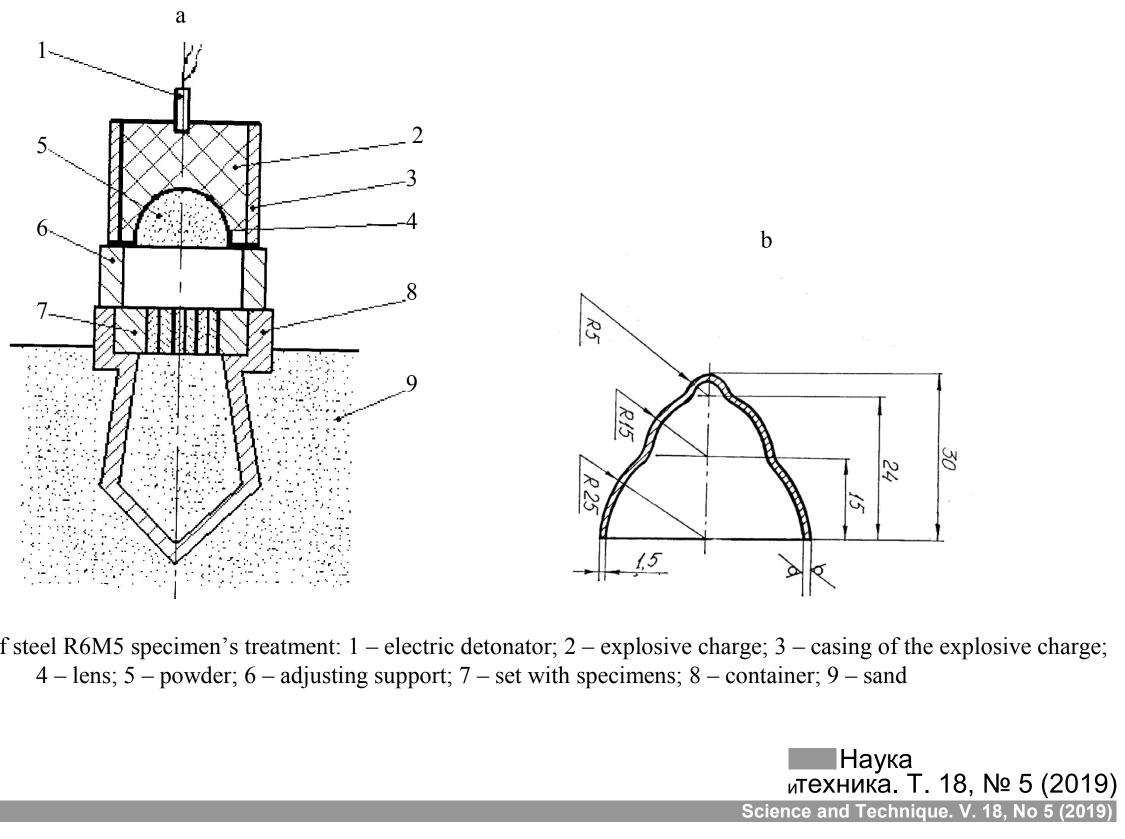


*Fig. 2.* Scheme of steel R6M5 specimen's treatment: 1 – electric detonator; 2 – explosive charge; 3 – casing of the explosive charge; 4 – lens; 5 – powder; 6 – adjusting support; 7 – set with specimens; 8 – container; 9 – sand

Dynamic alloying of quenched high-speed steel, which does not contain a certain amount of residual austenite in its structure, leads to cracking or destruction of products. It is caused by low plasticity of martensitic crystals. Cracking is also observed if a large amount of residual austenite (40–45 %) is retained in the structure of the steel. It associates with high structural stresses arising during quenching. The optimum amount of residual austenite at which dynamic processing becomes possible is approximately 20 % for tungsten-molybdenum steels and 25–30 % for tungsten-cobalt ones.

Thermal stresses arising in high-speed steel after quenching lead to cracking of the samples during dynamic processing. To reduce thermal stresses it is necessary to implement low-temperature tempering. Tempering, which is carried out at temperatures below 150 °C, does not lead to a decrease in hardness. Tempering at temperatures of (200–350) °C reduces hardness by 2–4 units of HRC.

Possible schemes of dynamic alloying of quenched high-speed steel were experimentally verified:

1. Repeated introduction of alloying particles with intermediate annealing. In this scheme, it is necessary to carry out annealing between the dynamic processing operations at a temperature above $\alpha \rightarrow \gamma$ transformation ((900–950) °C) to remove high structural stresses formed during quenching and dynamic alloying. During this treatment the processes of steel softening are intensively taking place. The experiments carried out showed a low efficiency of hardening during processing according to this scheme.

2. Simultaneous introduction of alloying particles in three mutually perpendicular directions. When processing in this scheme of high-speed steel in the annealing state, it is possible to ensure a uniform distribution of microchannels in the volume of products. As a result, there is the increase in the level of mechanical properties and elimination of their anisotropy. However, treatment in a quenched state leads to the destruction of steel products and therefore cannot be recommended.

3. Single introduction of alloying particles in a given direction (usually from the end surface). When processing according to this scheme, parts are placed at a certain distance from the explosive accelerator, and the explosive charge is detonated. This mode of particles introduction into the quenched high-speed steel is the most technologically advanced, because this scheme allows obtainning high-quality products and provides high manufacturability of the hardening process.

*Complex processing of quenched steel.* The combination of steel processing operations with high-speed particle flows and nitriding leads to the appearance of a surface layer with an unusual structure. Along with the solid nitrided layer of steel with a thickness of 40 to 60 microns, to a depth of 140 microns a layer of nitrided vertical columnar structures surrounded by areas of the original steel structure is formed (fig. 3).

The abrasive tests of samples with simultaneous impact loading showed that the samples hardened by complex technology have a wear resistance of 1.5–2.5 times higher than that of the original steel X12M and after diffusion nitriding.

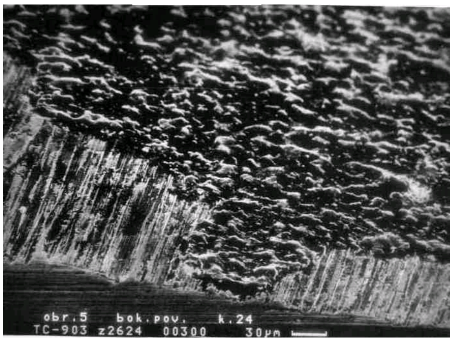


*Fig. 3*. Microstructure of the surface layer of steel X12M after treatment with a flow of particles and nitriding

Samples treated with a mixture of powders 50 % SiC + 25 % $Al_2O_3$ + 25 % $Si_3N_4$ showed the highest level of wear resistance (increase in 2–3 times). Their structure of nitrided zones was the most developed and the diffusion nitriding layer had depth up to 70–80 μm.

Dynamic alloying of materials by powder particles, in particular SiC, under the conditions of their penetration leads to the formation of a structure with many channels, different from the structure of the base material. The study of the fine structure by diffraction electron microscopy allowed us to establish that the channel zone consists of a central fiber zone with the remains of powder particles, which is surrounded by an amorphous zone of 8–10 μm wide. The amorphous zone passes into a nanocrystalline one with thickness of 15–20 μm with further transition into a micro-crystalline zone with thickness of about 30 μm, followed by a transition to the crystalline state characteristic of the matrix material.

The formation of channel structures is accompanied by intense plastic deformation, both due to the penetration of particles and the compression of the channel walls behind the particle. As a result, even with a single exposure, the material acquires properties characteristic for a composite material with a pronounced anisotropy. Amorphous-like elements of the structure are formed in narrow local areas due to the accumulation of energy that are resistant to thermal effects. As a result of research it was established that after shock-wave loading there is a grain refining by 1.8–2.5 times compared to structure of initial steel in the area of microparticles penetration.

Thus, the analysis of the obtained results allows us to conclude that the wear resistance of the tool steel X12M strengthened by the complex technology increases by 1.5–2.5 times. One of the reasons for the increase in wear resistance is the formation of a layer with the structure of the composite material, reinforced by channel zones, which play the role of reinforcing elements. The combination of methods of volumetric dynamic alloying by powders particles and surface treatment of parts by diffusion nitriding can by 2.0–2.5 times increase the performance of the die tool.

*Influence of particle flow treatment on the structure of tool steel*. The structure of high-speed steel after quenching consists of martensite, excess carbides, insoluble during heating under quenching, and residual austenite. In the structure of steel after etching, there is the presence of pores, which, obviously, are formed during the braking out of the carbide phase. Tool steel R6M5 was used as the processed material, which was subsequently applied for the cutting insert of cutters RKS-1 type for mining combines used for the production of potassium ore. Steel R6M5 has high mechanical characteristics in the initial state, and complex heat treatment is applicable to it providing dispersion hardening (fig. 4).

It is obvious that the preliminary treatment by the powder particles flow should affect the processes of diffusion redistribution of alloying elements and carbon in the structure of R6M5 steel during heat treatment and accordingly change its properties (fig. 5).

a

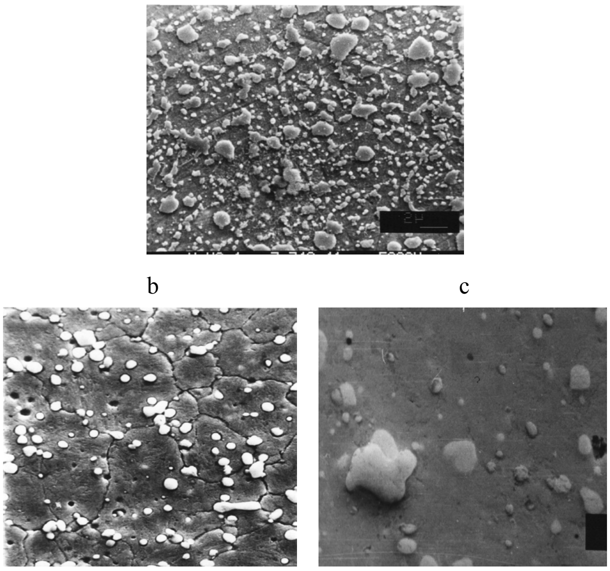


*Fig. 4*. Structure of the initial steel R6M5:
a – after annealing (×5000);
b – after quenching from 1220 °C (×2500);
c – after quenching from 1220 °C
and triple tempering at 560 °C (×2500)

a b

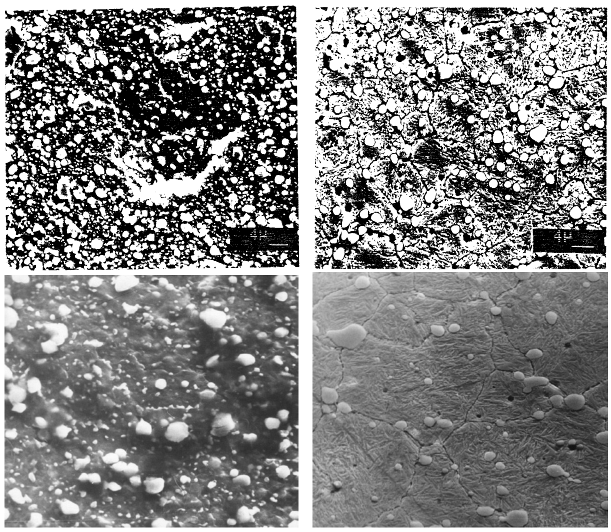

*Fig. 5*. The structure of steel R6M5 treated
by high-speed flow of Ni + SiC powders:
a – after annealing; b – after quenching from 1220 °C (×2500)

Dynamic micro-alloying of quenched steel does not lead to any noticeable changes in its structure. For example, the density and pore size do not increase, which emphasizes the complexity of the process of powder particles penetration into quenched steel. Steel etchability slightly increases and therefore it becomes possible to identify martensite in the structure. After a single tempering (at 560 °C) for one hour the formation of zones, which differ in etching and chemical composition is observed in the structure of high-speed steel R6M5K5 in a quenched state, subjected to dynamic alloying using a powder mixture Ni + SiC (fig. 6).

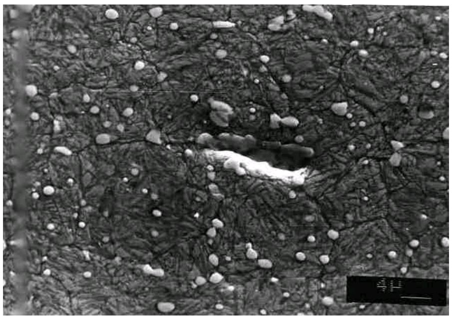


*Fig. 6.* Microstructure of steel R6M5K5 after a single tempering at $T = 560$ °C (etching in a 10 % solution of nitric acid) (×2500)

Studies conducted with a SEM "Stereoscan-360" with micro-X-ray spectral analysis allowed to establish that these zones contain an increased content of W and V, obviously, in the form of a carbide phase. At the same time, such alloying elements as Cr and Mo are evenly distributed between the matrix and the reinforcing zones (fig. 7).

The average size of the zones observed on the cross sections with respect to the direction of introduction of the alloying jet is 5–7 μm. With the increase in the duration of tempering the size of the reinforcing fibers increases and reaches 8–10 μm. Analysis of the steel structure in the hardening zone after a triple tempering at 560 °C (fig. 8) revealed the following.

In the center of the zone there is a significant amount of vanadium with the content ~45 % of all the studied elements, and there is no Nickel and Titanium. The presence of Nickel was recorded at some distance from the center, but the amount of vanadium (~3 %) was significantly reduced, and the content of the remaining alloying elements approached their average content in R6M5K5 steel. The formation of zones with a high content of vanadium carbide helps to increase the wear resistance of steel. Changes in the structure of the R6M5 tool steel occur because the particles flow impact and their penetration into the steel (fig. 9).

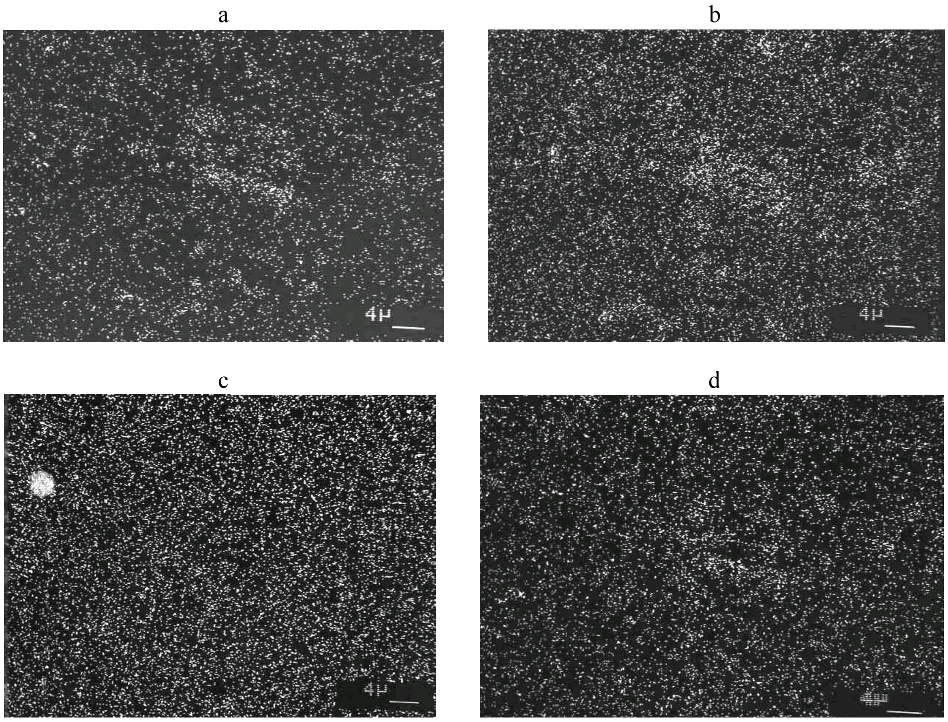


*Fig. 7.* Microstructure of steel R6M5K5 in characteristic radiation, (×2500):
a – tungsten; b – vanadium; c – chromium; d – molybdenum

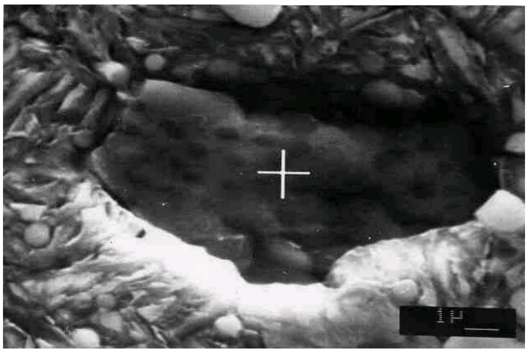

*Fig. 8.* Microstructure of steel R6M5K5 after triple tempering at $T$ = 560 °C (×10000)

a b

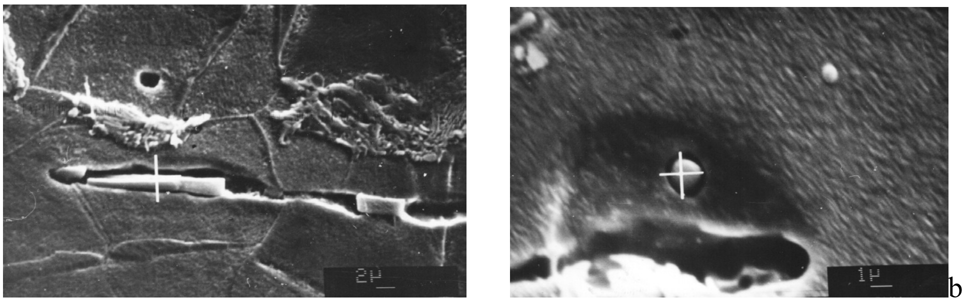

*Fig. 9.* Structural fragments of microparticles penetrated into the structure of steel R6M5 at a depth of 4 mm from the surface: a – longitudinal micro-section; b – transverse micro-section

Structures and properties of P6M5 steel in the initial quenched and non-quenched state are different. These features remain after processing by high-speed particle flow, as the influence of penetrating particles is different on structural components of steel. Penetrating particles form discrete fibers in the direction of penetration leading to anisotropy of properties. The treatment results in the increase in wear resistance in the transverse direction in 1.5–2.0 times.

Due to the shock-wave action there is a crushing and redistribution of carbide phases. As a result, the treated steel after standard heat treatment has a hardness of HRC = 58–64. Additional information about the influence of dynamic alloying on changes in the fine crystal structure of the tool steel was obtained by X-ray study. The data obtained are summarized in tab. 1.

*Table 1*

**Data on X-ray analysis of R6M5K5 tool steel**

| № specimen | Specimens studied | Lattice parameter, Å | Widening of lines, rad. $\times 10^{-3}$ | | Size of VCL, Å |
|---|---|---|---|---|---|
| | | | 110 | 220 | |
| 1 | Initial steel | 2,8693 | – | – | 4000 |
| 2 | Treated with aluminum oxide powder | 2,8709 | 2,7 | 7,7 | – |
| 3 | Treated with titanium carbide powder | 2,8726 | 2,9 | 10,1 | 3827 |
| 4 | Treated Ni + SiC powder mixture | | | | |
| | After quenching from 1220 °C and annealing at 560 °C | | | | |
| 5 | Without treatment with explosion | 2,8754 | 7,915 | 37,467 | 163 |
| 6 | Treated with $Al_2O_3$ powder | 2,8771 | 8,716 | 40,885 | 154 |
| 7 | Treated with TiC powder | 2,8774 | 9,028 | 40,663 | 136 |
| 8 | Treated with Ni + SiC powder mixture | 2,8776 | 8,580 | 40,553 | 146 |

As can be seen from Table 1, the parameters of the fine crystal structure of the initial material are changed under the influence of the particle flow. The change in these parameters depends on the material used to form the jet of the working substance. The crystal structure changes dramatically after quenching from a temperature of 1220 °C and a triple tempering at 560 °C. There is a decrease in the size of the blocks (areas of coherent scattering) and an increase in the relative micro-distortions of the structure leading to the lines broadening. The smallest block size is observed in the case of titanium carbide application and the largest increase in the micro-distortion of the structure is observed for the use of a silicon carbide + Nickel mixture.

### The influence of dynamic alloying on the hardness and wear resistance of quenched steel

Studies were carried out on samples made of R6M5K5 steel. Dynamic alloying was implementted using explosive accelerators with cylinder shape containers. Powders SiC + Ni, $TiB_2$ were used as alloying substance. The hardness of steel depends significantly on the modes of heat treatment and pulsed loading. The amount of residual austenite increases in the structure of high-speed tool steel with the growth in the heating temperature for quenching and, accordingly, the ability to harden increases. The average velocity of the particles in the jet is about 880 m/s for a cylindrical container with the powder (titanium diboride powder).

The hardness of the processed samples increases with the growth in the velocity of the particles in the powder jet, which is apparently due to an increase in the average pressure level of the shock waves arising from the collision with the surface of the processed specimens. The results of the hardness measurements of the samples after quenching and dynamic alloying are shown in tab. 2.

As can be seen from the above data, the maximum of the hardness increment of the parts processed by the explosion is observed when using an explosive accelerator with a container in the form of a cylinder and equal to 2.5 units HRC at a quenching temperature of 1240 °C. However, the use of this accelerator, which provides an increase in the particle speed and the average pressure level of the shock waves, greatly increases the cracking of the treated samples. As a result, it requires the use of special methods to prevent its occurrence. Probably more appropriate is the use of an accelerator with a container in the form of three docked hemispheres. The maximum hardness increase for samples of R6M5K5 steel is 2.0 units HRC. The latter circumstance is due to the influence of cobalt, which enhances the ability to harden the solid solution. It is very important to compare the effect of dynamic alloying on the increase in both hardness and wear resistance of high-speed tool steel.

Influence of dynamic alloying of quenched steel on its wear resistance was carried out on R6M5K5 steel samples with a diameter of 14 and a length of 50 mm. Dynamic alloying was carried out using an accelerator with a container in the form of three docked hemispheres. A mixture of Nickel and silicon carbide powders were used for alloying. Wear resistance tests were performed applying AI-1 unit with the following parameters:

– rotation speed of the counterbody (abrasive wheel) – 2.6 m/s;

– rotation speed of the test samples ~0.17 m/s;

– the number of simultaneously tested samples – 6 PCs.;

– specific pressure on the sample – $2 \cdot 10^5$ Pa.

The results of the wear tests are shown in tab. 3.

*Table 2*

**Data on specimens made of R6M5K5 steel**

| № specimen | Steel type | Mode of treatment | Heating temperature under quenching, °C | Hardness, HRCэ | |
|---|---|---|---|---|---|
| | | | | Hardened steel | Non-hardened steel |
| 1 | P6M5K5 | Quenching + Dynamic microalloying (SiC + Ni) with cylinder shape container | 1200 | 65,0 | 64,0 |
| 2 | P6M5K5 | The same | 1220 | 66,5 | 65,0 |
| 3 | P6M5K5 | The same | 1240 | 68,0 | 66,0 |

*Table 3*

**Wear resistance tests of R6M5K5 steel**

| № specimen | Heating temperature under quenching, °C | Relative wear resistance | Remarks |
|---|---|---|---|
| 1 | 1220 | 1,0 | Non-hardened steel |
| 2 | 1220 | 1,9 | Hardened steel |
| 3 | 1240 | – | Cracks were seen |

A comparison of the data in tab. 2 and 3 shows that there is no direct relationship between the hardness and wear resistance of the hardened steel. The maximum wear resistance is achieved by quenching from the temperature of 1220 °C, and the maximum hardness – by quenching from 1240 °C. This is probably because with an increase in the heating temperature under quenching the degree of martensite alloying and the amount of residual austenite increase, which is intensively riveted during shock wave processing. As a result, significant increase in hardness takes place. However, along with this, there is the formation of microcracks in the structure of steel after dynamic alloying, which determines the reduction of wear resistance. The wear resistance of steel hardened in the annealing state and subjected to further quenching from 1220 °C and tempering at 560 °C is 1.6 times higher than the wear resistance of non-hardened steel, but 20 % lower than the wear resistance of steel hardened in the quenched state.

The results of laboratory tests on the strength and wear resistance of high-speed steel R6M5 in the initial state and after treatment with high-speed flows of Ni + SiC particles are presented in tab. 4.

These tests of hardened R6M5 steel allowed to establish the optimal sequence of technological operations and to choose a hardening powder material in relation to the working conditions of the mining tool installed on the working bodies of the tunneling and purification potassium salt-mining combines. Cutting inserts (fig. 9) after the explosive processing were subjected to a triple tempering at 560 °C and subsequent grinding using centerless-grinding machine to obtain a certain diameter.

## The practical application of the method of dynamic alloying

Hardening of metals by the proposed method using explosives is a promising technology to improve the properties of parts made of tool steels and steels such as G13L. The hardness of the surface layer of parts made of G13L steel increases from HB 175–180 to HB 400. It is worth to note that the hardened by explosion steel has a greater ductility than after cold rolling. This is typical for other steels. For example, the impact strength of R6M5 steel after triple treatment increases by 20–30 %.

The service life of railroad arrow cross cores made of steel G13L increases in 2.0–2.5 times after treatment with the products of the explosion. As well, many parts for agricultural machinery are manufactured from the same steel. As an example, cutting parts for metalworking and for mining machines, the inserts made of tool R6M5 steel processed by dynamic alloying are shown in fig. 10. As a result of alloying, their wear resistance increased in 1.7 times.

Replacing the hard alloy with hardened R6M5 steel allows slightly change the size of the cutting tool. It is possible to reduce the insert diameter from 9.0 to 7.0 mm since the impact and bending strength of R6M5 steel are higher in comparison to the VK8 hard alloy. As a result, the energy consumption of the potash ore mining process becomes lower. The new material made it possible to abandon the traditional technology of fixing the insert and holder with soldering. The connection of the insert with the holder is carried out by pressing. Long length (26 mm) of insert allows increasing the number of tool regrinding during operation resulting in the reduction of maintenance cost.

*Table 4*

**Testing results on strength and wear**

| Material | Heating temperature under quenching, °C | Tempering temperature, °C | $\sigma_b$, MPa | Wear, mm/km |
|---|---|---|---|---|
| Initial steel R6M5 | 1210–1215 | 535–555 | 3820–3940 | 0,35–0,45 |
| Steel treated with SiC | 1180–1185 | 540–555 | 3820–3830 | 0,28–0,30 |
| Steel treated with Ni | 1210–1220 | 535–555 | 4210–4310 | – |
| Steel treated with SiC + Ni mixture | 1210–1220 | 580–600 | 4410–4560 | 0,18 –0,22 |

a b c

*Fig. 10.* Parts manufactured using the dynamic alloying method: a – metalworking cutters; b – cutters for mining machines; c – inserts

## CONCLUSIONS

1. It is established that dynamic alloying with SiC and $Al_2O_3$ powders leads to the formation of a specific structure of the composite material reinforced with channels consisting of a central fiber zone with powder particle residues. These channels are surrounded by amorphous area (8–10 μm), nanocrystalline one with fragmented cellular structure (15–20 μm), microcrystalline regions with transition to the crystalline state, characteristic of the matrix material of structural steel. The formation of such a structure leads to the increase in the wear resistance of X12M steel in 1.5–2.5 times and R6M5steel in 1.7 times.

2. It is established that the processes occurring in the material at the structural and substructural levels determine the effect of particles penetration into the material. Penetration of microparticles into the barrier is accompanied with the formation of microchannels in the barrier material. Such channels are visible by electron and optical metallography after cutting the specimens along the direction of particle movement.

3. It is established that in order to prevent cracking during the process of dynamic alloying of quenched steels it is necessary to conduct a preliminary low-temperature tempering after quenching.

4. Studies have shown that the wear resistance of high-speed steel subjected to dynamic alloying in the quenched state increases by 1.2 times compared to the wear resistance of steel alloyed in the annealing state (quenching and tempering modes are the same for these processing methods).

## REFERENCES


1. Fletcher A. C., Close S., Mathias D. (2015) Simulating Plasma Production from Hypervelocity Impacts. *Physics of Plasmas*, (22), 093504. https://doi.org/10.1063/1.4930281.
2. Fletcher A. C., Close S. (2017) Particle-in-Cell Simulations of an RF Emission Mechanism Associated with Hypervelocity Impact Plasmas. *Physics of Plasmas*, (24), 053102. https://doi.org/10.1063/1.4980833.
3. Chengzhi Qi, Jianjie Chen (2014) Physical Mechanism of Super-Deep Penetration of Solid Microparticles into Solid Targets. *Journal of Mechanical Behavior of Materials,* 23 (1–2), 21–26. https://doi.org/10.1515/jmbm-2014-0003.
4. Kozorezov K. I., Mirkin L. I. (1999) The Formation of Bulk Composites in Superdeep Penetration of Accelerated Solid Particles into Metals. *Physics and Chemistry of Materials Treatment,* 33 (3), 254–257.
5. Buravova, S. (2014) Superdeep Penetration Revisited. *Technical Physics*, 59 (8), 1257–1259. https://doi.org/10.1134/s106378421408009x.
6. Simonenko V. A., Skorkin N. A., Bashurov V. V. (1991) Penetration of Individual Microparticles Into Rigid Barriers on Collision of Powder Streams with Them. *Combustion, Explosion and Shock Waves*, 27 (4), 433–437. https://doi.org/10.1007/bf00789554.
7. Ovchinnikov V. I., Lobachev V. A. (2017) *Unit for Alloying by Explosion*. Patent Republic Belarus No u20160267 (in Russian).
8. Ovchinnikov V. I., Ilyushchenko A. F. (2014) *Unit for the Deposition of Material's Layer Onto Metallic Parts.* Patent Republic Belarus No u10271 (in Russian).
9. Zvorykin L. O., Usherenko S. V. (1993) Structural Features of Steel 45 after Interaction with High Velocity Flows of Niobium Boride and Molybdenum Silicide Powders. *Metallophysika = Physics of Metals*, 15 (1), 92–95 (in Russian).
10. Nozdrin V. F., Usherenko S. M., Gubenko S. I. (1991) Mechanism of Metals Strengthening During Super Deep Penetration of High Velocity Particles. *Physika i Khimiya Obrabotki Materialov = Physics and Chemistry of Treatment of Materials*, (6), 19–24 (in Russian).


Received: 30.05.2019
Accepted: 06.08.2019
Published online: 30.09.2019