Device for two-way cooling of rolls of multi-roll mills during laser hardening

***N. A. Chichenev**, Dr. Eng., Prof., Dept. of Engineering Technology Equipment [1],*
e-mail: chich38@mail.ru;
***M. V. Vasilyev**, Senior Lecturer, Dept. of Engineering Technology Equipment [1],*
e-mail: mv@karfidovlab.com;
***A. O. Karfidov**, Head of Dept. of Engineering Technology Equipment [1], e-mail: a.korf@mail.ru;*
***O. N. Chicheneva**, Cand. Eng., Associate Prof., Dept. of Engineering Technology Equipment [1],*
e-mail: ch-grafika@mail.ru

[1] National University of Science and Technology "MISIS" (Moscow, Russia)

Development of the automotive industry, electronics, aviation and other modern branches of science and technology has led to the need to produce thin (up to 0.01 mm thick) and the thinnest (up to 0.001 mm) high-quality band from high-alloy steels, non-ferrous and noble metals, obtained on multi-roll cold rolling mills. One of the main requirements for work rolls is a high and uniform hardness of the surface of the barrel after hardening, which should increase the wear resistance of the working layer, reduce the degree of its damage and, thereby, ensure the high quality of the rolled strip. An effective way to improve the quality of rolls with a diameter of up to 20 mm is surface laser hardening. In laser hardening of rolling rolls, a technological scheme was used, according to which the roll made a screw movement at preset speed relative to a fixed laser beam, which led to formation of a continuous screw track (spiral) of the hardened material on the surface of the roll. The minimal rotational frequency, at which uniformity of the active layer is observed, has been experimentally established, while laser hardening of samples with double-sided water jet cooling turned out to be the most effective. The design of a sprayer device for cooling of rolls during laser processing is proposed, which provides a uniform active layer along the entire barrel length and significantly reduces buckling of rolls. The technology for the manufacture of rolls has been developed, which makes it possible to obtain work rolls for multi-roll mills with high operational resistance, and to improve the technical and economic indicators of production of precision band. Tests of the rolls made of Kh9VMFSh steel after laser hardening on the mill 300 showed reduction in wear by 1.5-2.0 times compared to the standard volume-hardened rolls and reduction in roll consumption from 0.22 to 0.11 kg / t.
Key words: sheet rolling, multi-roll mills, rolling rolls, bands, chromium steels, laser hardening, cooling device.
DOI: 10.17580/cisisr.2023.01.08

Introduction

Constructions of modern machines, aggregates and other equipment in different industrial branches use rather often thin and thinnest (with thickness up to 0.01 and 0.001 mm respectively) precision bands from high-alloy steels and non-ferrous metals, which are manufactured in multi-roll cold rolling mills [1-5]. At the same time, the technical standard documentation includes rather high requirements to accuracy of geometrical dimensions and surface quality (such important indicators as longitudinal and transversal thickness deviation and flatness of bands can be mentioned here) [6-8]. Dimensions and material of rolled thin sheets have the effect on allowable accuracy deviations of finished products. As a rule, thickness deviation of rolled band is accepted less for more thick and less wide bands, usually it does not exceed 10 % from nominal thickness (sometimes it is not more than 1 %).

Technical and economical indicators of rolling in multi-roll mills depends mainly on reliability and durability of the main technological tool – work rolls, which have the diameter within the range from 10 to 120 mm, depending on destination and constructive features of rolling mill. It was established as a result of analysis of operating reliability of work rolls in multi-roll mills, that wear of their working surface is the main cause of their breakdown; it is connected with insufficient contact strength of roll barrels. Other defects are connected with bending and rotating deformation as well as volumetric strength, they have practically no effect on workability of work rolls. Thereby high and uniform hardness of hardened working surface of a roll barrel is considered as the main criterion of work roll quality in multi-roll mills, because it reduces wear of working layer and thus provides manufacture of rolled band with high quality of surface and geometrical dimensions. Choosing the material for fabrication of rolls for multi-roll mills requires taking into account also its technological properties (such as machinability by cutting, calcination ability etc. for steels).

Goal setting

Tool steels with high chromium content and sometimes hard alloys are mainly used as materials for rolls in multi-roll mills [9]. Steels with low chromium content (such as carbon and low-alloy steels) are characterized by low calcination ability and susceptibility to brittle destruction, and are not practically used due to their low wear resistance. It is recommended to use the steel of Kh9VMFSh type with high chromium content for manufacture of rolls for multi-roll mills, because such steel is characterized by deep calcination ability and possibility of achieving high hardness of work rolls surfaces, what provides good workability of these rolls under large contact loads [10]. Some constructions of multi-roll mills use also high-chromium steels of Kh12M and 110Kh12MF grades as material for work rolls.

Finishing heat treatment aimed on forming of martensite with required concentration of carbon and alloying elements, which provides achieving of preset values of hardness, heat resistance and calcination ability, is one of the factors for getting the required operating characteristics by work rolls. Additionally it is desirable to save fine austenite grains to prevent reducing of volumetric strength and toughness of steel during heating. Volumetric quenching, quenching after heating by high frequency currents and high-temperature thermomechanical surface treatment are usually used in manufacture of work rolls for multi-roll mills as a finishing heat treatment [11-13].

Surface laser hardening is considered as one of the most efficient methods for improvement of rolls quality with diameter up to 20 mm; it has the following advantages [14-19].

1. Provision of high hardness, wear resistance, heat resistance and fatigue strength.

2. Possibility of use of laser treatment as a finishing operation, because buckling and varying of geometrical dimensions of rolls are practically absent, and it allows to decrease labour intensity of mechanical processing and to increase fabrication accuracy.

3. High speed of austenitization and self-hardening, which provides obtaining of fine-grained martensite.

4. Possibility of easy adjusting of processing procedures in order to obtain the preset parameters of hardened alloy and local strengthening of working surfaces.

5. High productivity and possibility of laser processing automation.

It is shown in the works [20-25] that use of laser hardening of a roll barrel is rather efficient in manufacture of rolling rolls, because it leads to increase of service life of rolls and quality improvement of products. It is provided via creation of an active working layer with high physical and mechanical properties (such as hardness, heat resistance, contact fatigue resistance etc.).

Up-to-date level of laser equipment development allows to consider laser as a tool for conducting contact-free accelerated processing of materials independently to their mechanical properties. Laser emission, due to higher intensity of energy flow, provides more high speed of metal heating ($2\cdot10^3$ - 10^5 °C/s) than conventional methods of surface hardening of rolls (quenching after heating by high frequency currents, high-temperature thermomechanical surface treatment and quenching by line frequency currents). Thus, necessity of use of special quenching medium for forming the required microstructure is deleted, because efficient heat transfer from the surface (which was subjected to radiation) occurs due to interaction with internal metal layers; in this case average cooling rates during laser strengthening make usually 700-2000 °C/c.

That's why use of surface laser hardening as a finishing heat treatment during technological process of manufacture of work rolls for multi-roll mills increases their operating reliability and thus improves technical and economical indicators of thin and thinnest band production.

Obtained results

The main parameters the of strengthened layer (such as microstructure, hardness, depth of hardened layer, surface microgeometry etc.), which are obtained as a result of laser treatment, are determined by characteristics of continuous laser radiation (capacity, working period, diameter of laser beam etc.).

The special laser unit with gaseous CO_2-laser having radiation capacity up to 5 kWt, was created on the base of a screw-cutting lathe and used in these investigations. The roll that is subjected to laser hardening, is positioned in the rotating mechanism centers, is forced to rotate and is moved relatively to a laser beam. Thus, the roll makes practically screw motion relatively to a laser beam, while the period of laser beam effect can be adjusted within rather wide range by varying beam motion speed relatively to processing surface, owing to variation of roll rotation frequency and support stand travel speed. As a result, continuous screw path (spiral) of strengthened material with pace s_{sp} is forming on a roll surface; its value can be determined voa the formula:

$$s_{sp} = \frac{60\cdot V}{n} \text{ mm},$$

where V – speed of support stand motion of translation, mm/s;
n – frequency of roll rotation, min^{-1}.

Uniform values of hardness and depth of hardened layer along roll barrel length stipulate preference of equality between spiral pace s_{sp} and laser beam diameter d_b, i.e. $s_{sp} = d_b$, because if $s_{sp} > d_b$, then a layer of non-strengthened metal with width (s_{sp} - d_b) between the paths of strengthened metal, while if $s_{sp} < d_b$, overlapping of spiral convolutions occurs, which can lead to forming of tempering areas with reduced hardness. It is not desirable for rolls of multi-roll mills, which operate under high and varied loads; additionally, heterogeneity of physical and mechanical properties of working surfaces of rolls leads to deterioration of quality of rolled bands.

Investigations have shown that minimal frequency of rolls rotation n_{min}, which provides homogeneity of physical and mechanical properties of a surface layer along roll barrel length, depends on the speed of its translational motion and laser beam diameter. Quality of laser hardening was assessed by presence (or absence) of strips and uniformity of hardness values for the strengthened layer. Tempering areas for overlapping of spiral convolutions are

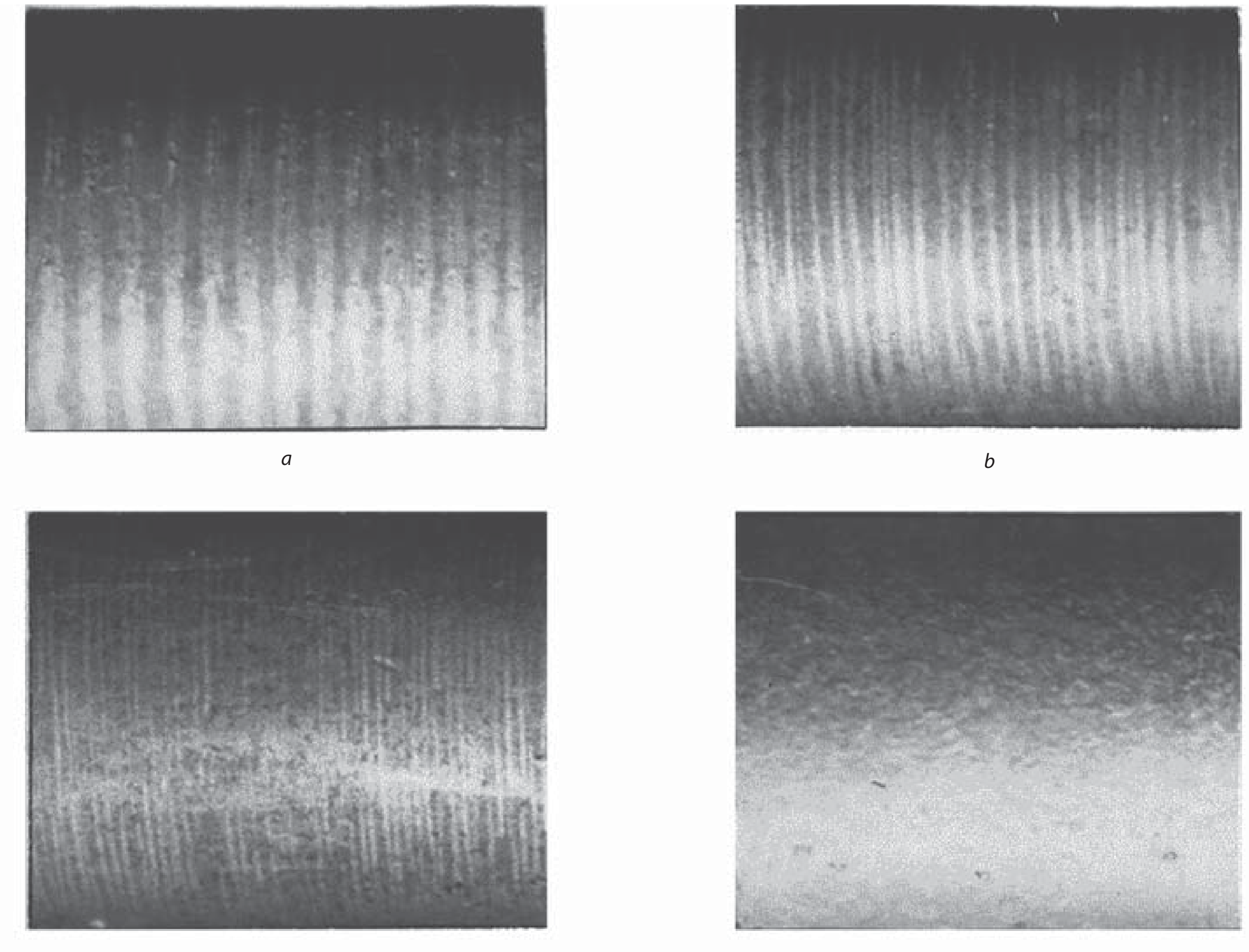

Fig. 1. Surface of the samples with diameter 15 mm made of steel Kh9MVFSh after spiral laser hardening at q = 30 kWt/cm², V = 3 mm/s, d_b = 2.5 mm and n = 100 (*a*), 300 (*b*), 700 (*c*) and 1500 (*d*) min⁻¹.

absent during homogenous laser hardening, while hardness gradient in the surface layers along the samples does not exceed 2 HRC units. Minimal rotation frequency that is necessary for uniformity of the active layer was established experimentally. Macro-pictures of the surface and dependencies of minimal rotation frequency, which provide uniformity of surface laser processing of rolls with diameter d_r = 15 mm after spiral laser hardening with specific capacity of laser radiation q = 0.3 kWt/mm², are presented on the **Fig. 1** and **Fig. 2** as examples.

Microstructure of the active layer of rolls during laser treatment consists of fine acicular martensite (97 %) and residual austenite (3 %), what increases operating parameters of rolls and improves strip quality. To obtain martensite structure during laser hardening, metal cooling speed should exceed the critical values for this metal.

It was established that laser hardening of small diameter rolls at small processing speeds is accompanied by undesirable heating of their core, which leads to their overheating. It is connected with the fact that the speed of heat distribution of laser radiation in a roll body exceeds the speed of laser spot travel along its axis. Thereby it is required to apply forced cooling of rolls near the laser processing area to avoid this disadvantage.

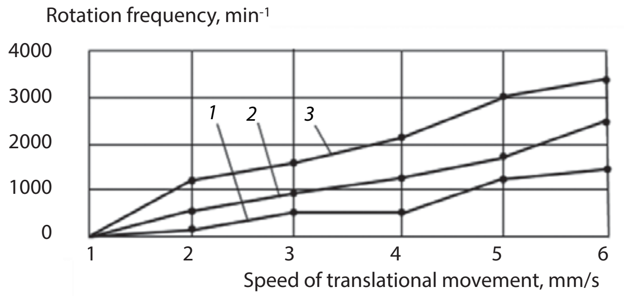

Fig. 2. Dependence between minimal rotation frequency, providing uniformity of surface laser processing of rolls with diameter d_r = 15 mm, and speed of translational movement, with specific capacity of laser radiation q = 0.3 kWt/mm² and laser spot diameter d_s = 3.5 mm (*1*), d_s = 3.0 mm (*2*) and d_s = 2.5 mm (*3*).

The jet water cooling method has become widespread practically; it provides high intensity of heat transfer and its rather simple adjusting via varying of cooling fluid consumption.

Three cooling routes, where cooling fluid (water) was fed in the area of laser heating on the processing surface via jet method using special devices (sprayers) are considered.

Table 1. **The values of hardened layer depth and surface hardness after laser hardening via different cooling routes**

Parameter	Cooling route			
	Route 1	Route 2	Route 3	Route 4
Depth of hardened layer, mm	1.5	1.0	2.0	0.6
Surface hardness, HRC	65-66	64-65	67-68	56-57

Comments. Route 1. Water supply to the entrance of the laser heating area.
Route 2. Water supply to the exit from the laser heating area.
Route 3. Water supply to the entrance and the exit of the laser heating area.
Route 4. Without cooling.

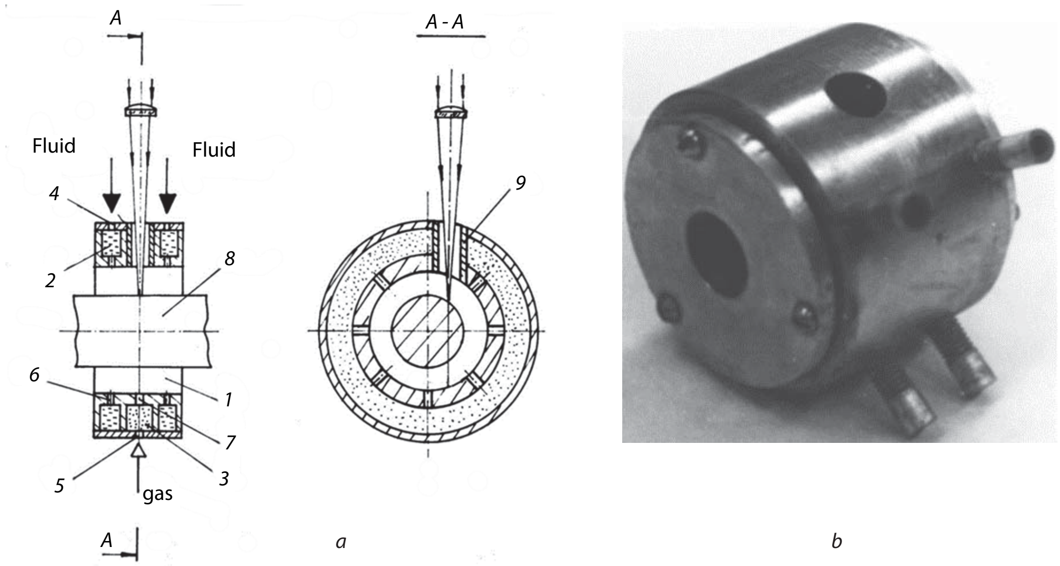

Fig. 3. Scheme (*a*) and external view (*b*) of the device for double-sided rolls cooling during laser hardening:
1 – shell; *2* – water supply chamber; *3* – gas supply chamber; *4* – entrance hole for water supply; *5* – entrance hole for gas supply; *6* – channels for water supply; *7* – channels for gas supply; *8* – roll; *9* – exit window for laser beam

The first route include water feeding only to the entrance of the laser heating area, the second route – only to the exit from the laser heating area, the third route was based on simultaneous water supply both to the entrance and to the exit of the laser heating area. Additionally, the experiments without supply of cooling water were conducted for comparison.

When conducting the experiments, the samples with diameter 15 mm and length 100 mm made of steel Kh9VMFSh were used. They were subjected to preliminary heat treatment – oil quenching from the temperature 1080 °C until achieving hardness 60-61 HRC. The above-mentioned cooling routes were analyzed for the following values of technological parameters of laser radiation: P = 3 kWt; laser spot diameter d_s = 2 mm; roll rotation frequency n =6000 min^{-1}; speed of translational motion V = 2 mm/s. Water consumption Q_W = 0.04 l/s was determined empirically. The experimental results are presented in the **Table 1**.

Analysis of the obtained data shows that the cooling route 3, providing laser hardening with water supply to the entrance and the exit of the laser heating area, was the most efficient one. More intensive cooling with double-sided water feeding finalizes in the fact that core temperature of billets does not vary practically the thereby does not influence on cooling rate of metal surface layers, which were heated up to the temperature of phase transformations.

To realize double-sided jet water supply (both to the entrance and the exit of the laser heating area), the special cooling device (sprayer) was developed, its construction is presented on the **Fig. 3**.

This device for double-sided cooling of rolls during laser hardening (sprayer) includes copper shell *1* with a hole (exit window) *9* for laser beam passing. At the same time, shell *1* plays also a reflecting function owing to its mirror internal surface, which increases laser treatment efficiency due to use of additional heating of roll surface by reflected laser radiation. Ring cavities (chambers) *2* and *3* respectively are constructed in the shell for supply of cooling water and protective gas. Water enters the chamber *2* through the entrance holes *4* and then it is fed on a roll through the exit channels *6* outside the laser treatment area. Gas enters the chamber *3* through the entrance hole *5* and then it is fed through the exit channel *7* in the laser treatment area. Necessity of gas (air or inert gas) supply to the laser treatment area is stipulated by protection of rolls surface and optical system elements from splashes of cooling water and burning products. Supply of cooling water and gas also helps in sprayer shell cooling during laser hardening. To prevent possibility of targeting reflected laser radiation in the laser optical system, axial direction of the entrance hole *9* is located under small angle to perpendicular of a roll barrel. It also helps to improve safety for the personnel, because exit of reflected laser radiation from the sprayer shell is impossible.

Practical valuability of this work consists of the fact that the obtained results were used for development of the technology for rolls fabrication, which includes the following operations: oil quenching from the temperature 1080 °C, laser hardening and tempering at the temperature 560 °C during 1 hour. It helps to achieve high hardness of an active layer (68 HRC), low level of residual stresses, increased heat resistance (60 HRC at the temperature up to 600 °C) and high ductility of rolls core.

Wear resistance of the steel Kh9VMFSh in the conditions of benchmark tests increases after laser hardening by 1.5-1.6 times in comparison with volume-hardened steel. High mechanical properties of the active layer promote rising of operating resistance by 2/1-2.5 times. Experience of operation of rolls made of steel Kh9VMFSh in the rolling mill 300, after their laser hardening, displayed decrease of wear resistance by 1.5-2.0 times in comparison with conventional volume-hardened rolls, and reducing of rolls consumption from 0.22 to 0.11 kg/t. No metal adhesion on the working surfaces of rolls was noted during rolling of thin (0.012x200 mm) brass strip. At the same time, the number of appearances of strip flatness defects reduced due to increased stability of roll shape. The number of strip bursting accidents decreased by 1.5-2.0 times, strip surface cleanness rises from 7th to 8th roughness grade.

Conclusion

The construction of device for jet cooling of rolls during laser processing was suggested; it provides obtaining of the uniform active layer along whole roll barrel length and substantial decrease of rolls buckling. The technology of rolls fabrication, which allows to manufacture work rolls for multi-roll mills with high operating resistance and to improve technical and economical indicators of precise band production, was developed.

Pilot-industrial tests of rolls made of steel Kh9VMFSh after laser hardening in the rolling mill 300 displayed decrease of wear resistance by 1.5-2.0 times in comparison with conventional volume-hardened rolls, and reducing of rolls consumption from 0.22 to 0.11 kg/t. No metal adhesion on the working surfaces of rolls was noted during rolling of thin (0.012x200 mm) brass strip. The number of strip bursting accidents decreased by 1.5-2.0 times, strip surface cleanness rises from 7th to 8th roughness grade.

REFERENCES

1. Jiang Z. Y., Wei D., Tieu A. K. Analysis of cold rolling of ultrathin strip. *Journal of Materials Processing Technology*. 2009. Vol. 209. No. 9. pp. 4584–4589.
2. Sheikhi Sh., Angerbauer A., Wuppermann C. D. Developments in flat strip production. *Chernye metally*. 2010. No. 1. pp. 30-37.
3. Ritterbach B. Trends in steel research. *Chernye metally*. 2014. No. 9. pp. 75-78.
4. Rumyantsev M. I. Some approaches to improve the resource efficiency of production of flat rolled steel. *CIS Iron and Steel Review*. 2016. Vol. 12. pp. 32-36.
5. Sudakov N. V., Pellenen A. P. Reserves in cold sheet rolling. *Metallurg*. 2018. No.11. pp. 47-51.
6. Tibar H., Jiang Z. Improving Thin Strip Profile Using Work Roll Cross and Work Roll Shifting Methods in Cold Strip Rolling. *International Journal of Metals*. 2017. Article ID 6489769., 10 p. DOI: 10.1155/2017/6489769.
7. Mazur V. L., Nogovitsyn O. V. Theory and Technology of Sheet Rolling: Numerical Analysis and Applications. CRC Press: Boca Raton, FL, USA, 2019. 494 p. DOI: 10.1201/9781351173964
8. Parshin S. V. Innovating solutions in constructions of 20-roll mills. A manual. Ekaterinburg: Izdatelstvo Uralskogo universiteta. 2016. 76 p.
9. On the results of conduction of anti-dumping investigation in relation to steel forged rolls for metal rolling mills, manufactured in Ukraine and imported to the common customs area of the Customs Union. Moscow: Evraziyskaya ekonomicheskaya komissiya. 2014. 82 p.
10. Bashnin Yu. A., Dzyuba V. A., Blokhin I. E. et al. Study of Kh-9VMFSh steel for contact and fatigue strength. *Izvestiya vuzov. Chernaya metallurgiya*. 1986. No. 7. pp. 105-106.
11. Polukhin V. P., Nikolaev V. A., Tylkin M. A. etc. Reliability and durability of cold rolling rolls. Moscow: Metallurgiya. 1976. 448 p.
12. Smirnov A. E. Management on phase composition of complex-alloyed heat-resistant steels during vacuum cementation and quenching. *Metallovedenie i termicheskaya obrabotka metallov*. 2020. No. 9 (783). pp. 45–52.
13. Metal science and heat treatment of steel and iron. A reference book I 3 volumes. Vol. 3. Heat and thermomechanical treatment of steel and iron. Edited by Rakhshtadt A. G., Kaputkina L. M., Prokoshkin S. D., Supov A. V. Moscow: Intermet Inzhiniring. 2007. 919 p.
14. Maharjan N., Zhou W., Zhou Y., Wu N. Underwater laser hardening of bearing steels. *Journal of Manufacturing Processes*. 2019. Vol. 47. pp. 52-61. DOI: 10.1016/j.jmapro.2019.08.020.
15. Khorram A., Davoodi Jamaloei A., Jafari A., Moradi M. Nd:YAG laser surface hardening of AISI 431 stainless steel; mechanical and metallurgical investigation. *Optics and Laser Technology*. 2019. Vol. 119. Article No. 105617. DOI: 10.1016/j.optlastec.2019.105617.
16. Bahrami Balajaddeh M., Naffakh Moosavy H. Pulsed Nd:YAG laser welding of 17-4 PH stainless steel: Microstructure, mechanical properties, and weldability investigation. *Optics and Laser Technology*. 2019. Vol. 119. Article No. 105651, DOI: 10.1016/j.optlastec.2019.105651.
17. Chichenev N. A., Gorbatyuk S. M., Naumova M. G., Morozova I. G. Using the similarity theory to describe laser hardening processes. *CIS Iron and Steel Review*. 2020. Vol. 19. pp.44–47.
18. Grigoryants A. G., Shiganov I. N., Misyurov A. I. Technological processes of laser treatment. A manual. Moscow: Izdatelstvo MGTU im. N. E. Baumana. 2006. 663 p.
19. Laser technologies of materials treatment: modern problems of fundamental and applied researches. Edited by Panchenko V. Ya. Moscow: FIZMATLIT. 2009. 664 p.
20. Polukhin V. P., Beletskiy V. V., Ivanov S. A. et al. Prospects of laser heat treatment application for hardening of working surface of rolls in multi-roll mills. *Metallurgicheskaya i gornorudnaya promeshlennost*. 1986. No. 6. pp. 33-34.
21. Veremeevich A. N., Beletskiy V. V., Ivanov S. A. On the problem of heat treatment of rolls in multi-roll mills. *Izvestiya vuzov. Chernaya metallurgiya*. 1986. No. 11. pp. 157-158.
22. Chichenev N. A., Chicheneva O. N., Karfidov A. O., Pashkov A. N. Selection of laser processing parameters for hot stamping tools based on mathematical planning of the experiment. *CIS Iron and Steel Review*. 2021. Vol. 22. pp. 37-40.
23. Bardovskiy A. D., Gerasimova A. A., Bibikov P. Ya. Principles of improvement of milling equipment. *Gornyi zhurnal*. 2020. No. 3. pp. 56-59.
24. Pinakhin I. A., Chernigovskiy V.A. Grounds of volumetric impulse laser strengthening of tool and structural materials. Stavropol: Izdatelstvo SKFU. 2014. 160 p. Available at: https://rucont.ru/efd/304170.
25. Aborkin A. V., Vaganov V. E., Shlegel A. N., Bukarev I. M. Effect of laser hardening on die steel micro hardness and surface quality. *Metallurgist*. 2015. Vol. 59. No. 7-8. pp. 619-625.