The effect of laser hardening on the operation resistance of rolls of multi-roll mills and the quality of the rolling strip

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The results of experimental studies of the process of laser hardening of rolls of multi-roll mills during linear and spiral hardening of samples from Kh9VMFSh steel are presented. It was found that during linear laser treatment, the depth of the hardened layer significantly depends on the power of laser radiation and the speed of translational motion of samples; at the same time, it weakly depends on the diameter of the laser beam. Corresponding graphs, which are more convenient for practical use for selection of technological modes of laser processing, have been built. With spiral laser hardening, the surface of axisymmetric parts is subjected to cyclic heating, the number of cycles of which depends on the speed of translational motion and rotation speed. It is established that decrease of the temperature of the surface layers of the part heated by laser radiation practically does not occur due to thermal conductivity at a sufficiently high value of the rotation speed. It is shown that increase of the rotation speed of samples from 1,000 to 10,000 min-1 leads to increase of the depth of the hardened layer from 0.72 to 1.60 mm with a slight enlargement of hardness of the surface layers, while the depth of the hardened layer significantly depends on the speed of translational motion of the samples and their diameter; it should be taken into account when developing technological modes of laser hardening. Pilot-industrial tests of working rolls during rolling of the strip with 0.012×200 mm cross-section, made from L63 brass, showed that the surface purity of the rolled strip increased from the 7th to the 8th class of roughness, and the number of breaks decreased by 1.5-1.8 times. When rolling a strip of nickel NP-2 at a 20-roll mill 300, it was found that consumption of rolls that have been subjected to laser processing is 2 times less than consumption of volume-hardened rolls, while transverse thickness has decreased to ± 3 % (compared with ± 5 % during rolling in volume-hardened rolls).

Key words: sheet rolling, multi-roll mills, rolling rolls, laser hardening, depth of hardened layer, hardness, rotation speed.
DOI: 10.17580/cisisr.2023.02.09

Introduction

The modern technical systems of different industries are characterized by wide use of thin and thinnest (with thickness to 0.01 and 0.001 mm respectively) precision bands from high-alloy steels and nonferrous metals, which are produced in multi-roll cold rolling mills [1-6]. Rather high requirements to geometrical dimensions and surface quality (among them such important parameters as longitudinal and transversal thickness deviation and flatness) are imposed to such bands [7-10]. As a rule, thickness deviation of rolled band does not exceed 10 % of nominal thickness, sometimes it is less than 1 %.

Operating resource of the rolls in multi-roll mills usually is not worked out during their one rolling campaign, because high requirements to precision of geometrical dimensions and surface quality of rolled strip cause often work roll change due to variations of roll barrel surface micro-relief. Thereby two variants of laser hardening of the surface layer are possible during fabrication of rolling rolls: thickness of active layer provides workability of rolls during the complete operation period, i.e. this thickness exceeds machining amount during regrinding (1) and thickness of active layer provides workability of rolls during roll changes, i.e. between regrinding operations (2). The second variant can be realized with the laser machine in a roll grinding area of the cold rolling shop. Advantage of this route concludes in possibility of barrel hardening of rolls without surface fusion, what allows fabrication of rolls with hardness HRC 70 and more.

Technical and economical parameters of the rolling process in multi-roll mills depends mainly on reliability and durability of the main technological equipment – work rolls, with their diameter laying within rather wide range from 3 to 152 mm, owing to destination and designing features of the rolling mill [11, 12]. Analysis of operating reliability of work rolls in multi-roll mills shows that wear of their working surface, connected with insufficient contact strength of a roll barrel, is the main cause of their breakdown. Other defects are connected with bending and torsion deformations, they practically have no effect on workability of work rolls in multi-roll mills. Thereby high and uniform hardness of quenched work surface of a barrel is the main criterion of their quality, because it decreases wear of the working layer and provides fabrication of rolled band with high quality of surface and geometrical dimensions. When selecting the material for manufacture of rolls for multi-roll mills, its technological properties (such as workability by cutting, hardenability etc. for steel) are taken into account.

Goal setting

The rolls of multi-roll mills are mainly manufactured from tool steels with high chromium content, and sometimes from hard alloys. The steels with low chromium content (such as carbon and low alloy steels), which are characterized by low hardenability and sensitivity to brittle destruction, are not used practically due to their low wear resistance. The steel grades such as Kh9VMFSh with high chromium content are often used for work rolls of multi-roll mills; deep hardenability and possibility of obtaining high hardness of working surfaces of rolls is considered as an advantage of this steel, it provides their good workability in the conditions of large contact loads. High-chromium steel grades Kh12M and 110Kh12MF are also used in several constructions of multi-roll mills as material for work rolls.

Finished heat treatment aimed of obtaining martensite structure with the required concentration of carbon and alloying elements is one of the main factors for acquiring the necessary operating parameters by work rolls. This heat treatment is usually presented by volumetric quenching, quenching after heating by high frequency current and high-temperature thermomechanical surface processing [13, 14].

Surface laser quenching is recognized among the most efficient methods for quality improvement of rolls with diameter up to 20 mm. This method is characterized by the following advantages [15-19]: provision of high hardness, wear resistance, heat resistance and fatigue strength; possibility of use as a final operation due to absence of buckling and variation of geometrical dimensions of rolls, what allows to reduce machining workability and to improve fabrication accuracy; slight tuning of processing procedures in order to achieve the required parameters of the quenched layer and local hardening of working surfaces; high productivity and possibility of process automation. It is shown in the works [20-22], that use of laser hardening of a roll barrel is efficient in the process of work rolls fabrication; it leads to increase of surface life of rolls and quality improvement of products. It is achieved via creation of the active layer with high physical and mechanical parameters (such as hardness, heat resistance, contact fatigue resistance etc.).

The achieved level of development of laser machinery and technologies allows to consider laser as a tool for realization of contactless high-speed materials processing independently to their mechanical properties. Laser radiation provide more high speed of metal heating ($2\cdot10^3$ - 10^5 °C/s) in comparison with conventional methods of surface quenching of rolls, due to high intensity of energy flow. Thereby necessity of use of the special quenching medium for forming the required microstructure disappears, because efficient heat removal from radiated surface occurs due to interaction with internal metal layers; at the same time average cooling speed values during laser hardening make 700 - 2000 °C/s.

Thereby use of surface laser quenching as a final heat treatment of technological process for manufacture of work rolls in multi-roll mills increases their operating reliability and, respectively, improves technical and economical parameters of production of thin and thinnest band.

Obtained results

The main technological parameters that determine the depth of the hardened (quenched) layer h_{quen} during laser processing are the following ones:

- density of laser radiation, which is equal to relation of laser radiation power P to surface square under this radiation $A = \pi\cdot(d_s)^2$, where d_s is a diameter of the spot of focused laser beam;
- speed of laser bear transition along the roll surface V.

Additionally, reflecting capacity of the processing surface, thermal physical parameters of the material, application method for laser tracks (in particular, it is necessary to take into account rotation frequency of rolls n during spiral laser processing) etc. have influence on laser processing.

Our researches included examination of influence of laser hardening on operating resistance of rolls and quality of rolled strip during linear and spiral quenching of the samples from Kh9VMFSh steel, which is often used for fabrication of rolls in multi-roll mills.

Table 1. **Values of depth of the hardened layer of hquen for various modes of laser processing of samples made of Kh9VMFSh steel**

Laser radiation power P, kWt	Depth of the hardened layer h_{quen}, mm for speed of translational motion of samples V, mm/s					
	5	10	20	30	40	50
1.0	1.58	1.15	0.85	0.70	0.60	0.50
1.5	2.06	1.45	1.00	0.84	0.72	0.62
2.0	2.21	1.70	1.20	0.95	0.81	0.70
2.5	2.62	1.91	1.34	1.11	0.95	0.80
3.0	2.85	1.95	1.47	1.27	1.01	0.90

To determine depth of the hardened layer h_{quen} during laser linear processing, flat samples from Kh9VMFSh steel, with size 12x20x100 mm were used; these samples were subjected to preliminary heat treatment (oil quenching at the temperature 980 ºC and tempering at the temperature 160 ºC), they are characterized by hardness 35-37 HRC. Study of the relationship between h_{quen} (from one side) and speed of translational motion of samples V (from 5 to 50 mm/s) and laser radiation power P (from 1 to 3 kWt) (from other side) were carried out in the conditions of the constant diameter of laser spot d_s = 1.5 mm (**Table 1**). The measuring error for h_{quen} value made ±10 μm. Experimental results displayed that depth of the hardened layer h_{quen} depends essentially on laser radiation power P and speed of translational motion of samples V.

The empiric relationship between depth of the hardened layer and technological parameters of laser processing was obtained after mathematical treatment of the experimental results. Based on this, the graphs of relationship between depth of the hardened layer and speed of translational motion were built (**Fig. 1**), it is suitable to use these graphs practically for selection of technological procedures of laser processing.

To assess the influence of laser beam spot dimensions d_s on depth of the hardened (quenched) layer h_{quen}, the experimental studies with the constant radiation power (P = 2.5 kWt) and three values of the speed of translational motion (V = 8, 12 and 20 mm/s) were conducted. The laser beam spot diameter ds was varied within the range 1-7 mm via tuning of defocusing degree of a radiation beam. It is shown, that the h_{quen} value slightly depends on the laser beam diameter for the above-mentioned technological parameters; in this case it achieves its maximal value with d_s values which don't depend on the conditions of laser processing (**Fig. 2**).

The samples with diameter 10, 15, 20 and 30 mm from Kh9VMFSh steel, which were preliminary subjected to oil quenching from the temperature 980 ºC with achieving hardness 60-61 HRC, were used for determination of depth of the hardened layer h_{quen} during spiral laser processing.

The surface of axisymmetric parts during spiral laser processing is subjected to cyclic heating, unlike linear laser processing; the number of cycles can be determined via the firmula

$$Z_{heat} = \frac{n \cdot d_s}{60 \cdot V} = \frac{d_s}{s_{sp}}$$

where Z_{heat} – number of heating cycles; d_s – laser spot diameter, mm; V – speed of translational motion, mm/s; n – rotation frequency of a part, min^{-1}; s_{sp} – spiral pitch, mm.

If the number of heating cycles $Z_{heat} > 1$, then the next laser spiral track is laid on the previous one, i.e. laser tracks are overlapped, what can lead to material softening in heat treated part area. If the number of heating cycles $Z_{heat} < 1$, then there is a gap equal to $s_{pit} = s_{sp} - d_s$ on the part surface between adjacent laser tracks.

In general case, the graph of relationship between temperature and time is a combination of the heating and cooling cycles, i.e.

$$t_c = t_{heat} + t_{cool},$$

where t_c = 60/n – time of one cycle, s; t_{heat} – heating time, s; t_{cool} – cooling time, s.

During the time period theat, consumption of laser radiation power and metal heating occur during passing the thermal influence area by laser radiation, and during the time tcool, cooling occurs due to heat removal from the surface by cold layers of the part core. Size of this thermal influence area is determined by the spot diameter. Varying the frequency of part rotation n, we can adjust the cycle time and respectively change heating and cooling time. It was established that lowering of the temperature of the part surface layers, which were heated by laser radiation, does not take place practically via thermal conductivity at rather high n value. It allows to consider the spiral laser processing as a heat treatment process for the part by continuous power flow.

The experimental results of assessment of the frequency of part rotation n on the depth of the quenched layer h_{quen} and

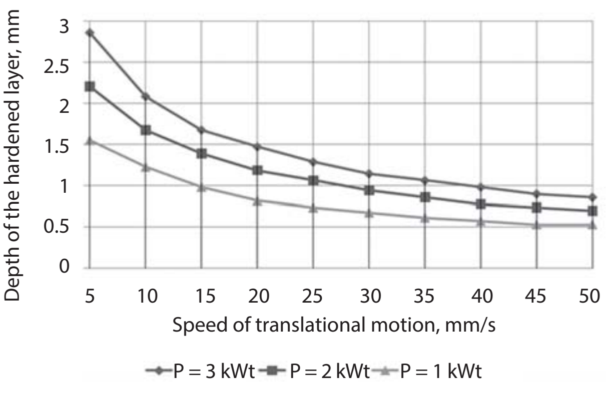

Fig. 1. Dependence of depth of the hardened layer on speed of translational motion and power of laser radiation during linear hardening of rolls made of steel Kh9VMFSh

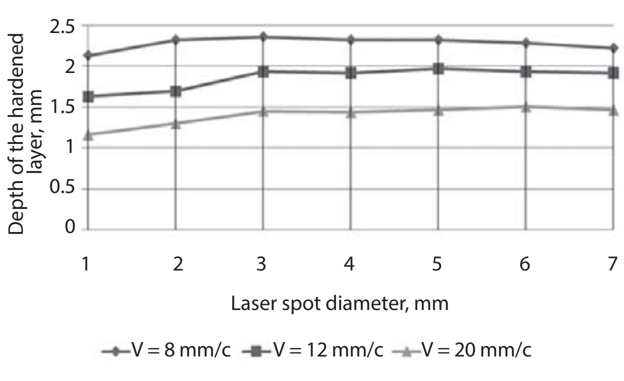

Fig. 2. Experimental dependencies of depth of the hardened layer on the diameter of laser beam spot and the speed of translational motion (steel Kh9VMFSh; P = 2.5 kW)

its hardness of the samples with diameter 15 mm and length 100 mm from Kh9VMFSh steel are presented as the example in the **Table 2**. The study was carried out at the constant values of radiation power (P = 3 kWt) and speed of translational motion (V = 2 mm/s), while part rotation frequency was varied within the range 1,000-10,000 min^{-1}. Measurement error of h_{quen} value made ±10 µm. It is shown that increase of rotation frequency of samples from 1,000 to 10,000 min^{-1} leads to enlargement of the depth of the quenched layer from 0.72 to 1.60 mm, accompanied with small rise of hardness of the surface layers.

After mathematical processing of the obtained results, the empiric relationship between the depth of the quenched layer h_{quen} and the frequency of part rotation n for the samples was found out; according to this relationship, it is possible to determine the value $h_{quen\,2}$ for the frequency of rotation n_2 of samples using the known value $h_{quen\,1}$ which was obtained at the frequency of rotation n_1.

$$h_{quen2} = h_{quen1}\frac{\left[1 - e^{-\sqrt[3]{\frac{n_2}{60}}}\right]^8}{\left[1 - e^{-\sqrt[3]{\frac{n_1}{60}}}\right]^8}$$

To assess the influence of laser radiation power on the depth of the hardened (quenched) layer hquen, the experimental studies were conducted on the samples with diameter 10 and 15 mm, for two speeds of translational motion (V = 2 and 4 mm/s), constant values of rotation frequency of these samples (n = 1,0000 min^{-1}) and laser spot diameter (d_s = 1.5 mm). Analysis of these experimental data displayed (**Table 3**) that the depth of the quenched layer h_{quen} is directly proportional to square root of laser radiation power during spiral processing. Thereby, after determination of the quenching depth value h_{quen1}, we can calculate the quenching depth value hquen2 for radiation power P_2

$$h_{quen2} = h_{quen1} \cdot \sqrt{\frac{P_2}{P_1}}$$

To assess the influence of the speed of translational motion and diameter of samples on depth of the quenched layer, the samples with diameter 10, 15, 20 and 30 mm were hardened at the constant values of radiation power (P = 3 kWt), rotation speed (n = 1,0000 min^{-1}) and spot diameter (d_s = 1,5 mm) (**Table 4**). The experimental results displayed that the depth of the quenched layer hquen depends significantly on the speed of translational motion of thr samples and on their diameter, what should be taken into account on the process of development of technological conditions for laser hardening. At the same time, hardness of the surface layers is varied slightly.

When rolling the band in multi-roll mills, theoretical resource of service life of work rolls is never worked out due to their quick wear. The work rolls of the 20-roll rolling mill 300, which were manufactured via conventional technology,

Table 2. **Values of the depth of the quenched layer hquen and hardness of samples from Kh9VMFSh steel after spiral laser treatment with different rotation speed values (P = 3 kWt, V = 2 mm/s).**

Frequency rotation, min^{-1}	Laser quenching parameters	
	Depth of quenched layer, mm	Surface hardness, HRC
1,000	0.72	64-65
2,000	1.00	64-66
3,000	1.20	65-66
4,000	1.36	65-66
5,000	1.38	65-67
6,000	1.40	66-67
7,000	1.40	66-67
8,000	1.43	66-68
9,000	1.52	67-68
10,000	1.60	67-68

Table 3. **Values of depth of the quenched layer hquen and hardness of samples from Kh9VMFSh steel after spiral laser treatment with different radiation power**

Initial data			Experimental results	
Diameter of samples, mm	Translational motion, mm/s	Radiation power, kWt	Depth of the quenched layer, mm	Surface hardness, HRC
10	4	1.0	0.76	68-69
		1.5	1.24	67-68
		2.0	1.45	65-66
15	2	1.0	0.82	68-70
		2.0	1.26	67-68
		3.0	1.50	67-68

Table 4. **Values of depth of the quenched layer hquen and hardness of samples from Kh9VMFSh steel after spiral laser processing with different speed of translational motion**

Initial data		Experimental results	
Diameter of samples, mm	Translational motion, mm/s	Depth of the quenched layer, mm	Surface hardness, HRC
10	4	1.21	67-68
	3	1.41	65-66
	2	-	-
	1	-	-
15	4	0.98	68-69
	3	1.17	67-68
	2	1.47	67-68
	1	2.01	66-67
20	4	0.63	68-69
	3	0.78	67-68
	2	1.00	67-68
	1	1.50	65-66
30	4	0.23	69-70
	3	0.30	68-69
	2	0.44	67-68
	1	074	67-68

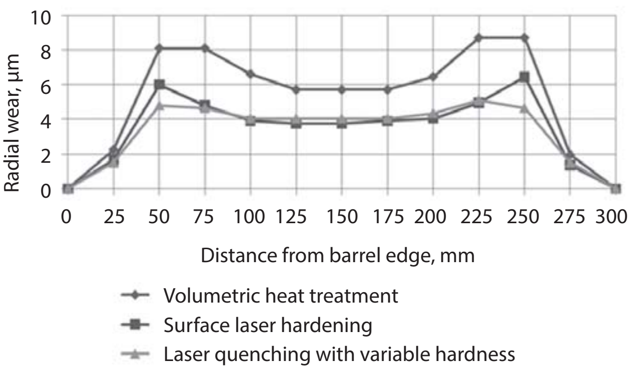

Fig. 3. Barrel wear curves of work rolls of the mill 300 with diameter 15 mm after 4,000 cycles

are subjected to 15,000 loading cycles during their operation in the rolling stand. At the same time, the service life resource for such level of contact stresses exceeds 50 mln. cycles. Thereby, there is a reserve for increase of operating service life of work rolls in a rolling stand owing to rise of their wear resistance.

Micro-relief of roll barrel surface gets new configuration during operation process owing to non-uniform distribution of wear value along the length. Roll surface wear is determined by its hardness and microstructure, as well as metal sensitivity to strain hardening, friction conditions, barrel shape etc. Surface laser quenching has influence on operating resistance of rolls via variation of metal physical and mechanical properties. In order to examine the effect of laser hardening of rolls resistance and strip quality during rolling in multi-roll mills, comparative industrial tests with nickel NP-2 strip rolling in the 20-roll mill 300 were carried out. The rolls from steel Kh9VMFSh were used, which were hardened via laser quenching and volumetric heat treatment. The testing results displayed that consumption of rolls, being subjected to laser quenching, is less than consumption of volume-quenched rolls by 2 times.

The features of barrel wear of rolls along their length is the same both for laser quenching and volumetric heat treatment (**Fig. 3**).

The wear curves were obtained via statistical processing of the measurement results of the wear values for the rolls of both types, which were operated in the same conditions. The wear value in the barrel areas corresponding to the edge of rolled strip is maximal and makes 6.3 µm for the rolls which were hardened by laser radiation, and 8.9 µm for the volume-quenched rolls. Wear in the middle part of barrels is minimal, its value makes 3.8 µm and 5.8 µm respectively. It is shown that rolling stability increased and transversal thickness deviation lowered to ± 3 % (in comparison with ± 5 % for rolling in volume-quenched rolls) as a result of use of laser hardened rolls.

Conclusion

The results of experimental investigations of the process of laser hardening for rolls of multi-roll mills via linear and spiral quenching of the samples from Kh9VMFSh steel are presented.

It was established that depth of the quenched layer during laser processing depends substantially on laser radiation power and speed of translational motion of samples; at the same time it weakly depends on laser beam diameter. The corresponding graphs were built, which are suitable to be used practically for selection of technological procedures of laser processing.

During spiral laser quenching, the surface of axisymmetric parts is subjected to cyclic heating, with number of cycles depending on speed of translational motion and rotation frequency. It was revealed that lowering of temperature of the part surface layers, which were heated via laser radiation, practically does not take place via heat conductivity at rather high value of rotation frequency. It is shown that increase of rotation frequency of the parts from1,000 to 10,000 min^{-1} leads to increase of the depth of the quenched layer from 0.72 to 1.60 mm with a slight enlargement of hardness of the surface layers, while the depth of the quenched layer significantly depends on the speed of translational motion of the samples and their diameter; it should be taken into account when developing technological modes of laser hardening.

Pilot-industrial tests of working rolls during rolling of the strip with 0.012×200 mm cross-section, made from L63 brass, showed that the surface purity of the rolled strip increased from the 7^{th} to the 8^{th} class of roughness, and the number of breaks decreased by 1.5-1.8 times. When rolling a strip of nickel NP-2 at a 20-roll mill 300, it was found that consumption of rolls that have been subjected to laser processing is 2 times less than consumption of volume-hardened rolls, while transverse thickness has decreased to ± 3 % (compared with ± 5 % during rolling in volume-hardened rolls).

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