Journal of Physics: Conference Series

PAPER • **OPEN ACCESS**

Investigation of the possibilities of surface hardening of heavily loaded metal elements made of carbon steels for various purposes

To cite this article: A E Moldahmetova *et al* 2022 *J. Phys.: Conf. Ser.* **2388** 012055

IOP Publishing
2388 (2022) 012055 doi:10.1088/1742-6596/2388/1/012055

Investigation of the possibilities of surface hardening of heavily loaded metal elements made of carbon steels for various purposes

A E Moldahmetova[1], T E Sarsembaeva[2], I M Vasil'ev[3], R R Zagidullin[4], L S Sabitov[4,5], A F Nurullin[4] and S V Novikov[4]

[1]Eurasian National University named after L.N. Gumilyov, Astana, Republic of Kazakhstan
[2]Kazakhstan Agrotechnical University named after. S. Seifullin, Astana, Republic of Kazakhstan
[3] LLC PKF Alliance, St. Petersburg, Russia
[4]Kazan Federal University, Kazan, Russia
[5]Kazan State Power Engineering University, Kazan, Russia

E-mail: aliya-981@mail.ru

Abstract. The interaction of the wheel and the rail, being the physical basis for the movement of trains, determines not only such important technical and economic indicators of railway transport as the weight of trains and their speed, the reliability and operational life of wheel sets, but also the basis of the foundations of railway operation - the safety of train traffic. Therefore, studies of the problems of interaction of the wheel-rail friction pair are relevant and in demand not only within the framework of a particular wagon or locomotive depot, but also in the country's railway transport as a whole. In this regard, it is important to note that one of the main and most loaded elements of the undercarriage of locomotives and wagons that directly interact with the rails are railway wheels. An important factor in the development and implementation of new surface hardening technologies is: firstly, rising prices and corresponding costs for the production of metal products for wheels with high energy consumption, secondly, increasing costs for spare parts, maintenance and overhaul of wheel sets; thirdly, the rise in prices for energy carriers and transportation costs for their delivery; traditional heat treatment is almost impossible to achieve.

1. Introduction

An analysis of the current state of wheel sets of freight cars entering the planned types of repair and current (uncoupling) repair shows that the main reason for wheel turning is the wear of the tread surface. According to this defect, up to 50% of the wheels are turned. A significant number of wheels (up to 35%) fail due to brake and thermal damage. Under heavy loads and high train speeds, thin surface layers of metal are heated to temperatures exceeding critical points (Ac_1, Ac_3) and, with subsequent accelerated cooling, the formation of solid, at the same time brittle, martensite, which leads to cracking of the surface layers of the wheel rim. In recent years, to solve this problem, innovative technologies have been actively used using highly concentrated energy flows (plasma hardening), characterized by ultra-high heating and cooling rates and short exposure to the metal (10^{-2}–10^{-4}c). [1-3] As preliminary results of experiments show, during high-speed heating and cooling, the desired structures and properties of the metal are most often achieved due to the formation of certain metastable (nonequilibrium) phases and structures. This strongly affects the processes of nucleation and growth of austenite grains, its homogenization and decomposition upon cooling. As a result, the final structures of the surface layer of the steel are heterogeneous in chemical composition, structure, and physical and mechanical properties. Therefore, with this method of strengthening, non-equilibrium processes are of particular importance, which are important, and in some cases decisive, in the formation of the final structure and properties of the material. Given this circumstance, in this project the expected results will be considered, discussed and scientifically substantiated based on this specific provision of plasma treatment [4,5].

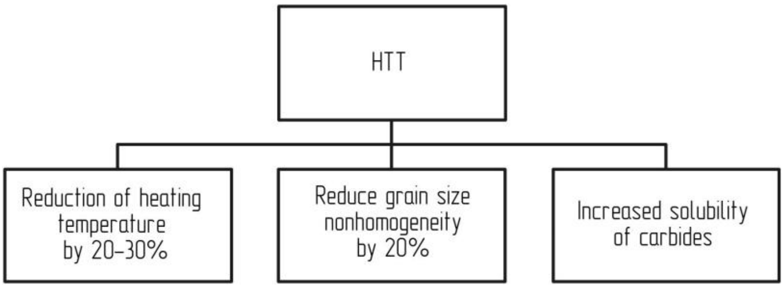
2. Materials and methods of research

To improve the performance properties, solid-rolled wheels are subjected to hardening heat treatment during the production process. In this case, the increase in strength occurs due to a strong grinding of the grain size of the steel and an increase in the degree of dispersion of carbides. An increase in resistance to plastic deformation (wear) is also achieved by obtaining structures with lamellar carbides during heat treatment. It follows that in order to increase the wear resistance of solid-rolled wheels, it is necessary to heat treat them in such a way that finely dispersed lamellar austenite decomposition products and a fine-grained structure of steel are obtained in all layers of the wheel rim. Studies performed using an electron microscope show that the structure with the maximum resistance to wear and fatigue failure is thin-lamellar pearlite, which is formed as a result of the decomposition of austenite at a certain relatively low cooling rate. At the same time, the structure of granular perlite formed as a result of rapid cooling (quenching) of steel for martensite and subsequent tempering, which has the shape of rounded grains, has lower wear resistance and low fatigue fracture resistance. Along with the size of the pearlite grain, dispersion and shape of carbide particles, the service properties of the transport metal, in particular, solid-rolled wheels, are significantly affected by the presence of precipitates of structurally free ferrite around the pearlite grains. Studies on samples of solid-rolled wheels cooled from the hardening temperature at different rates (hardness of 13 HRC, 19 HRC and 23 HRC were obtained) showed that as a result of accelerated cooling, the precipitation of structurally free ferrite along the boundaries of pearlite grains is suppressed and an increase in the entire complex of mechanical properties. It follows from these provisions that the initial structural state of the wheel has a significant effect on the structure and properties of the hardened layer and, thus, on the quality of plasma hardening.

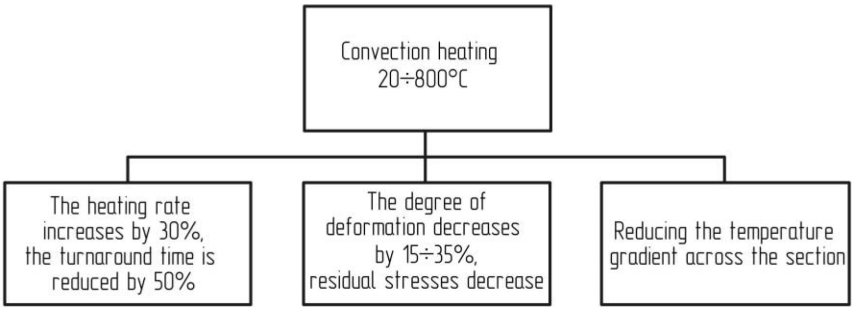
Plasma technologies are among promising hardening processes that can be used in the manufacture of heavily loaded metal elements. The increase in wear resistance using plasma processes can be carried out in two ways:

1) obtaining the required structure and properties in the surface layer by plasma hardening (without changing the composition of the material);

2) creation of a surface layer with a new chemical composition and structure that differs from the base material (Fig. 1).



A - scheme of the influence of HTT on the parameters of heat treatment and the structure of steels



B - scheme of the influence of convection heating during HTT on the processing parameters and the degree of deformation of products

Figure 1. Influence of High-Temperature Heat Treatment on Structure Parameters and Degree of Deformation.

The logic of the development of laser technologies leads to the need to use CAE (engineering computer analysis) tools both in the creation of equipment for laser processing of materials and in the development of specific technological processes. The question of quality is also very important when creating technological processes for processing highly concentrated energy sources. The use of SAE tools makes it possible to ensure guaranteed quality even at the stage of technology development. The basis for the creation of StrAU tools are reliable thermophysical and mathematical models of laser processing processes.

When radiation is incident on the interface between two media, the phenomena of reflection, absorption, and transmission are observed. For metals, in a very thin near-surface layer (several micrometers), the light remaining after reflection is absorbed. Therefore, the processes of volume absorption of radiation and its transmission during laser heat treatment are not considered. For metals, the optical properties of which can be described using the free electron model, the absorption of light quanta by conduction electrons is mainly characteristic. As a result, the energy of the electrons increases, which is transferred to the crystal lattice and other electrons. This process develops at a depth of 10^{-7}-10^{-6} cm in a very short period of time 10^{-11} - 10^{-10} s. Gradually, the temperature of the electron gas and the crystal lattice is equalized, i.e. after about 10^{-9} - 10^{-8} s, the concept of the total temperature of the metal T can be introduced. Energy is transferred from a thin surface layer to the bulk of the material by thermal conductivity. In this case, the surface temperature is of decisive importance. The reflectivity of metals depends on the state of their surface and the wavelength of the laser radiation - long-wave radiation is reflected more strongly. An essential circumstance is the decrease in reflectivity with increasing temperature of the treated surface. In addition, the absorption capacity of metals is affected by the nature of the power density distribution in the focal spot, the directivity and the angle of convergence of the beams. However, the power density level (q_0) of laser radiation in the treatment zone has a decisive influence on the absorption capacity. At power density levels $q_0 = 10^8...10^9$ W/m^2, there is an active local heating of the metal to a certain quasi-stationary state, at which there is still no noticeable evaporation of the material. In this case, it can be assumed that, depending on the degree of radiation concentration, a point or distributed source of heat with a power density q_p acts on the surface of the treated body. Such a heating source is usually used for heat treatment of surfaces without flashing and with flashing, surfacing, alloying: $q_p = A \times q_0$, where A is the effective coefficient of surface absorption (R=1–A is the reflection coefficient). At the melting temperature of many metals and power density $q_0=10^8$ W/m^2, the absorption coefficient A = 0.5, and when approaching the boiling point and q0=109 W/m2, the absorption approaches 0.75.

Absorption of laser radiation energy and its transition to thermal energy in the surface layer, which occurs almost instantly, lead to a sharp increase in the temperature of the material in the laser impact zone. At the same time, there is also an outflow of heat into the depth of the material. The temperature distribution on the material surface usually corresponds to the spatial distribution of the laser radiation intensity in the cross section. The study of high-intensity thermal processes of hardening in a wide range of parameters changes leads to the need to study complex nonlinear problems of heat transfer. The presence of nonlinearities is associated with temperature dependences of the thermophysical characteristics of the material, with phase transitions, with variations in boundary conditions, and other reasons. To determine the configuration of characteristic structural zones during laser hardening, direct problems of thermal conductivity are usually solved (most often by numerical calculation of temperature fields when parts are heated by a moving heat source) followed by analysis of thermal cycles at various points. Physical modeling is almost always carried out in natural conditions to confirm mathematical models or select technological modes and, therefore, does not require the involvement of similarity methods.

3. Results and discussion

Plasma hardening increases the hardness of the surface layer, red hardness, toughness, including the parameter of dynamic fracture toughness.

Table 1. Properties of R6M5 steel after treatment with a highly concentrated plasma jet.

Type of processing	HV	$К_{p58}$, °C	КCV	$a_{з}$	$К^{d}_{1c}$*, H/mm$^{3/2}$
			J/cm²		
Plasma jet treatment: total heat jet power 32 kW, 3 cycles	1070-1085	685	16	13	282
Volumetric heat strengthening	820-845	615	10	7	179

Notes. Volumetric heat treatment mode - hardening from 1220 °C in oil, tempering - 550 °C, 3 times for 1-hour cooling on air.
* $К^{d}_{1c}$ – criterion of dynamic fracture toughness.

The properties of the surface hardened layer are affected by the initial properties of the alloys.

The influence of volumetric hardening modes on the properties of steels 90HF and R6M5 subjected to additional plasma hardening (specific thermal power of the plasma jet $1.2 \cdot 10^{5}$ W/cm²; processing speed - $5.6 \cdot 10^{-3}$ m/s) are given in Table 2.

Table 2. Properties of steels 90HF and R6M5 at different heating temperatures during hardening.

Steel	Mechanical properties	Bulk hardening temperature, °C		
		800	850	900
90HF	HRC	46/65	58/68	59/69
	$\sigma_{в}$, MPa	600/400	870/650	800/600
	φ,%	2.5/3.9	2.3/3.5	2.1/3.4
R6M5		1170°C	1220 °C	1270 °C
	HRC	62/67	64/68	65/66.5
	$\sigma_{в}$, MPa	1500/2000	1500/3050	1100/2000
	φ,%	2.2/1.9	2/1.8	1.8/1.5
	$\sigma_{в}$, MPa*	2500	2400	2300

Note. The numerator shows the properties after bulk quenching and tempering, the denominator shows the properties after additional plasma treatment (to assess the properties of the surface layer, microsamples cut from the hardened layer of a massive workpiece were tested).
* Properties are given after volumetric hardening, plasma treatment and three volume tempering.

The heat resistance of R6M5 steel after plasma treatment (PT) is given in Table 3 [6-8].

Table 3. Heat resistance of R6M5 steel under various processing conditions.

Processing modes	The hardness of steel after holding at temperatures, °C			
Volumetric hardening from temperatures, °C:	600	650	700	750
1120	50	48	47	46
1220	62	57	55	54
1220+PT	67	65	58	56
1270+tempering +PT	68	66	63	57

Plasma treatment, carried out after preliminary volumetric hardening, steel, increases its mechanical and operational properties, red hardness. The highest values of strength and hardness are achieved after bulk hardening from optimal temperatures. Additional plasma treatment improves the properties of steel even if hardening was carried out at elevated temperatures.

Plasma treatment, carried out after CHT (nitrocarburizing in a solid medium) with the fusion of a tool made of steel 20X13 along the cutting edges and edges, provides an increase in hardness in the treatment zone (Table 4). Processing was carried out on a PKhK-M plasma torch with scanning edge melting.

Table 4. Plasma Treatment Modes and Properties of the Hardened Zone of Steel 20X13.

Tool Pretreatment	Layer thickness, μm*	Zone processing conditions	Weight loss, $\times 10^{-3}$mg	Microhardness, H**	impact strength, J/cm²
Nitrocarburizing 940 °C, 4 h; cooling at a rate of 300 °C/min	$\frac{800}{20-25}$	Plasma, argon, spot diameter 1.4 mm; δ_{edge} = 300-400 μm, 1 pass	7.6-8.1	$\frac{870-905}{980-1060}$	$\frac{35-44}{56-60}$

* The denominator shows the value of the surface zone of internal oxidation.

** The numerator shows the value of hardness after nitrocarburizing and tempering at 180-200 ºC for 2 hours, the denominator - after additional plasma treatment.

After nitrocarburizing, before plasma treatment, it is planned to remove the surface layer with a thickness of 10-30 μm. A tool that has undergone additional plasma or laser treatment with reflow, after tempering and diamond finishing, has increased wear resistance compared to nitrocarburized steel (Table 5).

Table 5. Tool wear resistance after plasma treatment.

Tool type	Cutting mode			R_a μm	Wear resistance relative *
	V_{cut}, mm/min	T,mm	S_{ser}		
Flat threaded insert Δ - 4 mm, L - 40 mm from 20X13, subjected to nitrocarburizing + plasma treatment, for cutting ABN ceramics	60-75	0,4-0,6	0,05-0,1	1,30-1,60	1,5

* In comparison with nitrocarburized and hardened from nitrocarburizing temperatures steel 20X13; HRC - 62-63.

Vacation should be carried out after plasma treatment, before and after finishing or diamond sharpening of cutting elements at 250-350 °C.

Laser hardening provides an increase in the hardness of steels compared to conventional hardening due to the grinding of martensite crystals and an increase in the dislocation density (during pulsed laser hardening of steel 45, the dislocation density reaches $30 \cdot 10^{10}/cm^2$, after the usual $0.3 \cdot 10^{10}/cm^2$). During laser processing with reflow of eutectoid and hypereutectoid carbon steels in the reflow zone, in addition to fine-grained martensite, residual austenite is present: in steel U8 - 39%, and in steel U10 - up to 45%. For this reason, the hardness of U10 steel is lower than U8, but remains high due to phase hardening. The microhardness of steel varies with the depth of the hardened layer - the laser impact zone (LIA) (Table 6). On steels U8 and U9, processing was carried out with flashing to a depth of ~ 50 μm by continuous laser radiation with a power of P = 1 kW (the speed of the laser beam was v_l - 1.7 mm/s). At the same time, microhardness increases at a depth of ~ 0.35 mm, on U12 steel, also in the annealed state, depending on the speed of the laser beam (the depth of the hardened zone ranges from 0.15-0.60 mm).

Table 6. Change in microhardness with respect to the depth of the laser impact zone steel U8, U9 and U12.

Steel	$v_л$, mm/s (m/min)	H_{50}, at a distance from the surface, mm									
		0	0.05	0.1	0.15	0.2	0.25	0.3	0.4	0.6/0.65	0.9
U8	1.7	1070	-	-	-	1000	-	350-410	350-410	-	-
U9		1000	1150	950	890	1000	620	550	550	-	550
U12	(0.6)	1000	1000	1000	1000	1000	1000	1000	1000	1000 300	300
	(1.8)	-	1050	1050	1050	1100	1200	1100	300	300	300
	(4.2)	-	1200	1000	1000	300	300	300	-	-	-

Laser heat hardening is promising for improving the performance properties of woodworking tools. Laser processing of steels was carried out on a gas laser EFA-53, P = 2.5 kW (American corporation "Coherent General") and the Bulgarian laser "Hebr"-1, P = 1.3 kW, at a speed of the laser beam from 10-60 mm/s.

4. Conclusion

Plasma treatment, carried out after preliminary volumetric hardening, steel, increases its mechanical and operational properties, red hardness. The highest values of strength and hardness are achieved after bulk hardening from optimal temperatures. Additional plasma treatment improves the properties of steel even if hardening was carried out at elevated temperatures. Laser hardening of eutectoid, hypereutectoid carbon, alloyed and especially high-alloyed tool steels does not always provide the necessary hardness of the surface layer, which is associated with the presence in the steel structure, in addition to martensite and carbides, of a significant amount of residual austenite (up to 40-60%). To reduce it, after laser hardening of the hardened surface, the entire part is cooled in liquid nitrogen or another medium that provides cooling of steel of this grade to a temperature below the end point of martensitic transformation. During cryogenic treatment, the amount of residual austenite in the hardened layer decreases, which leads to an increase in microhardness in the surface layer and a decrease in wear compared to laser hardening.

Acknowledgments

Research is carried out under the project AP14869891 "Improving the service life of heavily loaded parts of railway transport using innovative plasma technology."

This work was supported by the Strategic Academic Leadership Program of the Kazan (Volga Region) Federal University ("PRIORITET-2030").

References

[1] Bogdanov V.M., Zakharov S.M. 2014 Modern problems of the wheel-rail system. *Railways of the World* **1** 57-62.

[2] Balanovsky A.E. 2016 Main issues of plasma surface hardening of metals (Review. Part 3). *Hardening technologies and coatings* **2** 20-30.

[3] Sosnin N.A., Ermakov S.A., Topolyansky P.A. 2013 *Plasma technologies. Guide for engineers*. St. Petersburg: Publishing House of the Polytechnic University 403 p.

[4] Kanaev A, Bogomolov A, Sarsembaeva T. 2017 Overall Hardening of Solid-Rolled Wagon Wneels by Volume Quenching and Surface Plasma Processing. *Solid State Phenomena* **265** 706-711.

[5] Kanaev A. T., Bogomolov A.V., Kanayev A.A. 2018 Increase of Wear Resistance and Contract-Fatigue Strength of Wheel Steel by Plasma Hardening. *Materials Engineering and Technologies for Production and Processing* 1V, Trans Tech Publications, Switzerland 1144-1150.

[6] Vorobieva G.A., Skladnova E.E., Leonov A.F., Erofeev V.K. 2003 *Tool materials. Part 2. Modern methods of hardening tool materials: Reference manual*, Balt. state tech. un-t. SPb., 86 p.

[7] Remshev E.Y., Danilin G.A., Vorob'eva G.A., Silaev M.Y. 2015 Ensuring the operational reliability of elastic elements by acoustic methods. *Metallurgist Vol. 59* **3-4** 225-228.

[8] Remshev E., Rasulov Z., Voinash S., Vornacheva I., Sokolova V., Dolmatov S.N., Kolesnikov P. 2022 The evaluation effect of the active lubricating coating on the mechanical properties of stamped semi-finished products made of refractory metals. *Materials Science Forum* 3-10.