Application of plasma surface quenching to reduce rail side wear

M V Konstantinova¹, A E Balanovskiy¹, V E Gozbenko², S K Kargapol'tsev³, A I Karlina¹, M G Shtayger⁴, E A Guseva¹ and B O Kuznetsov³

¹ Irkutsk National Research Technical University, 83, Lermontov Street, Irkutsk, 664074, Russia
² Angarsk State Technical University, 60, Chaykovskogo Street, Angarsk, 665835, Russia
³ Irkutsk State Transport University, 15, Chernyshevsky Street, Irkutsk, 664074, Russia
⁴ MC Mechel Steel, 1, Krasnoarmeysky Street, 125167, Moscow, Russia

E-mail: karlinat@mail.ru

Abstract. Hardening of the side surface of the rail head with the use of optical and electron microscopy is studied. Results of industrial tests are given. Plasma hardening of the side surface of the rail allows one to obtain a favorable structure of the surface hardened layer (mixture of troostite, bainite and martensite) with a hardness of 450-830 HV and a thickness of the quenched layer of 2.5-3 mm. Thus, this significantly increases the service life of the rails due to the 2-3-time decrease in the wear rate of the side surface of the rail. The developed unit for plasma surface hardening of the rail allows performing qualitative surface hardening in width, depth and hardness of the surface layer of the metal. This equipment can be recommended for further pilot-industrial plasma surface hardening of the rail side surface in the conditions of the East Siberian Railway.

1. Introduction

During the wear process in the "wheel-rail" pair, both the wheel (rolling, flange wear) and the rail (vertical and side wear of the head) are getting damaged. The value of side wear of rails and wheel flanges is especially large when the train moves in curvilinear track sections (so-called curves) due to the striking of flange against the rail. In this regime, rolling and sliding movements are superimposed. The flange of the wheel slides along the lateral side of the rail head while the bandage is rolling along its rolling surface [1-3]. As a result, in the contact zone of the flange and the side surface of the rail head, there is an increase in shear stresses [2,3] which are much greater than the stresses in the rolling zone, and as a result, there is an increased wear of the rail. This problem is especially severe for those roads that have transhipping areas with a radius of curves R <600m. In such areas, the rails are replaced 3-4 times more often than on rectilinear track sections. To reduce side wear rate, it is proposed to increase the hardness of the side surface of the rail head in the contact zone of the rail and the flange of the wheel pair with the help of various methods of surface and volumetric heat treatment, cladding, spraying, and hardening [4-6]. In recent years, highly concentrated heating sources (laser beam, electron beam, plasma jet) [5,6], which allow improving the physicomechanical properties of the metal surface, increasing the service life of parts and reducing the cost of their repair, are widely used to harden surfaces of metal...
products. In [5], a technical and economic analysis of the methods of heat treatment by highly concentrated heating sources of the rail surface was made. It was shown that plasma heating is the most cost effective and productive one. It is characterized by lower capital and operating expenditures, accessibility and relative simplicity of technological equipment and large dimensions of the hardened zone (width – up to 60 mm, depth - up to 4 mm), differentiated surface hardness, etc. It is known [5] that surface hardening has a number of advantages if comparing with the volumetric one. This is because of lower energy costs, it is necessary only for heating the surface layer, and significantly lower heat stresses and residual deformations of parts, and also contributes to reducing the probability of fatigue failure of a part during operation. This article is devoted to the assessment of possibility of plasma surface hardening of the rail side surface with regard to the conditions of the East Siberian Railway.

2. Results and Discussion
The purpose of the work is to practice optimal regimes of plasma hardening of the rail and carry out operational tests in the conditions of the East Siberian Railways.

Accoring to [5], it is preferable to harden the surface with a plasma arc of direct action to harden the side surface of rails in the area of the wear zone in accordance with the technical and economic indicators. To carry out research on plasma hardening of the rail side surface, an experimental plasma stripper [5] has been developed in the INRTU for hardening the rail with a heat power of 6 kW.

This unit includes a power supply for the main and pilot arc, a remote control, a trolley with a platform for fastening the plasmatron, a plasmatron, a balloon unit with plasma-forming gas (argon), a bench with carriage guides and rail placement. All characteristics of the plasma arc (current, voltage, gas flow) were displayed to digital analyzers. When the main arc is ignited, current intensity increases gradually, not instantaneously and increases in the time interval of 3-5 seconds that allows preventing the flashing-off of the surface [5]. Current is regulated by the remote control, which can be changed in the range of 20-100 A. The limit for regulating the movement rate of the plasmatron along the rail is 0-45 m/h. Thermal action on the surface of the rail head was carried out by a plasma arc at various values of current, voltage, and movement rate of the plasmatron. To test the preliminary optimal parameters of plasma hardening, samples of M76 rail steel (GOST RF 51685-2000) [7] were made to study the action of a plasma arc on the surface of the rail head. Investigation of the results of the action of the plasma arc on the structure of the samples was carried out in two dimensions: along the surface and into the interior of the sample up to the basic structure. Photographing of the sample structures was carried out on metallographic microscope MIM-7, and on an electronic scanning microscope JIB 4500 (Jeol Ltd, Japan). Transmission electron microscope Tecnai G2 20F S-TWIN FEI. Microhardness was measured on a PMT-3 instrument. Selection of parameters for a specialized unit was carried out by varying the plasma arc current, working gas flow rate, movement rate of the plasmatron, and the distance from the lower surface of the plasmatron to the side surface of the rail.

The determination of the optimum value of the current intensity. The current varied in the range of 38-115 A. Gas flow rate, hardening distance, current intensity on the magnetic system, rate of hardening were constant. With a current intensity of 38-45 A, the arc was burning unstably, the track is discontinuous (Figure 1). The hardness of such sections does not exceed 420-440 HV. As the current increases from 90 to 115 A, sub-melts are formed along the entire length of the track (Figure 2), whose hardness is 930-1030 HV. The optimal current regime during experimental work was established in the range of 60 -85 A. The determination of the optimum value of argon flow rate. If argon flow rate is below 4.01/h, the plasma arc on the rail surface is burning unstably, the quenching process is interrupted, burns occur when a gas flow rate is above 7 1/h (Figure 3). During experimental work, it was established that the preliminary optimal gas flow rate is 5.5-6.5 l/h.

The determination of the optimal value of length of the plasma jet. The increase in the width of the track of the hardened layer is achieved by changing the magnetic field created by the electromagnet and is correlated with the length of the arc. The length of the plasma jet varied in the interval of 10-30 mm. With an arc length of 28 mm, width of the hardening track was 30 mm, hardening depth was 2.1 mm (Figure 4 and 5).
Figure 1. Track after plasma hardening at low current (38-45A).

Figure 2. Defects after hardening at increased current (90A).

Figure 3. Defects after hardening at high gas flow rate.

Figure 4. Macrostructure of the sample metal in the hardened zone (martensite) and the hardness of HRC at a current intensity of 85A and arc length of 28mm (width of the hardened layer is 30 mm, depth is 2.1 mm). Hardness of the base metal is HB 363.

At a length, equal to 15 mm, the width was 14-18 mm. When the length of the jet is increased to 25 mm, specific gas flow rate increases and the value of the current increases, while an unstable distribution with macro and microhardness along the width of the track is detected. Studies showed that when a jet length is 18-22 mm, a uniform distribution of hardness along the width of the track was observed, and the scanning of the arc was stable.

Figure 5. Macrostructure of the sample metal in the hardened zone (martensite) and the hardness of HRC at a current intensity of 85A and arc length of 28mm (width of the hardened layer is 30 mm, depth is 2.1 mm). Hardness of the base metal is HB 363.

Determination of the optimal value of the movement rate of the plasmatron. During the experimental work, it was established that the value of the surface hardness also depends on the movement rate of the plasmatron relative to the longitudinal axis of the rail. When movement rate of the plasmatron is 40-45 m/h, hardness of the hardened track is 875-940 NV, at rates of 30-35 m/h, hardness values were 800-865 NV, at rates of 18-25 m/h, hardness values were 740-800 NV.

With a length, equal to 22 mm, width of the hardening track was 26 mm, plasma arc current was 85 A (Figure 6a). With a length of 22 mm, having increased the current by only 5A (90A), width of the hardening track is 24 mm, and the depth increased to 3.1 mm and signs of micro-melting of the surface appeared (Figure 6b).
Figure 6. Microstructure of the sample metal, HRC hardness, arc length is 20mm: a – width of the hardened layer is 26 mm, depth is 2.6 mm; b – width of the hardened layer is 24 mm, depth is 3.1 mm, hardness of the base metal is HB 363.

When the slope angle of the plasmatron changes from 90° to 45° to the side surface of the rail, a discontinuous scanning of the arc with a slope to one side and a failure of hardening along the center of the zone occurs, instability of the hardening process is observed, and a considerable discrepancy of the hardness along the width of the track is observed. From the point of view of uniform scanning along the side surface of the rail head, the optimum angle is 90°. Complex of undertaken studies and experimental works on hardening of the wear zone of the side surface of the rail on the pilot unit made it possible to determine the preliminary optimal regimes and parameters of hardening by the plasma arc. To confirm the choice of experimentally established optimal regimes of plasma hardening, a study of a hardened layer of rail steel (hardness measurement, microstructure analysis, full-scale tests) was carried out.

The determination of the optimum slope angle of the plasmatron to the side surface of the rail. It was found that the location of the plasmatron should ensure uniform scanning of the arc heating spot along the side surface of the rail head. The direction of the plasmatron is schematically shown in Figure 7.

Under these conditions, a uniform track of hardening the wear zone of the side surface of the rail was achieved, there are no burns and metal flows (Figure 8).

Figure 7. Location of the plasmatron to the side surface of the rail head.  
Figure 8. State of the side surface of the rail head after hardening.

Metallographic study. The conducted studies showed that the structure of the hardened layer consists of a mixture of troostite, bainite, residual austenite and martensite in different quantitative ratio. The measurements of Vickers hardness and microhardness in depth of the hardened layer as a whole confirmed the results of preliminary measurements of hardness by a portable hardness testing
instrument. The hardness in the hardened layer varied within the limits of 590-915 HV. Metallographic studies showed that the depth of the quenched layers on the samples is 2-3.5 mm. Microstructure of the surface layer of the rail after plasma quenching consists mainly of martensite, Vickers hardness is HV10 803-924. The main component (~ 93%) in the structure of the matrix of quenched steel is the α-phase, which is characterized by the following values: crystal lattice parameter – 0.28702 nm, static atomic displacements - 0.02 nm, second kind microstress level – 650-710 MPa. Structure of the α-phase is a mixture of massive (or lath), lamellar (low-temperature and high-temperature) martensite and bainite (Figure 9). Massive (or lath) martensite occupies the main part of the α-matrix (~ 80%). Lamellar martensite is the second independent morphological type of the α-matrix of the studied rail steel [5]. A feature of this type of martensite is that it represents separately located martensite crystals – plates, which, as a rule, do not form parallel bunches, which is observed in massive martensite. The transverse size of the plates is larger than the transverse size of a single river by approximately an order of magnitude and amounts to ~ 1-3 μm. The separate martensitic plates are of two kinds: 1) large plates, length of which reaches 10-15 μm, 2) small plates with length - 0.5-1.5 μm. Large plates lie at some angles to each other and pervade almost all the grain.

![Optical microscope](a) ![Electron microscope](b) ![Transmission electron microscope](c)

![HZ](d) ![TZ](e) ![TZ](f)

**Figure 9.** The structure of the hardened layer of rail steel using various methods of metallography. Arrows indicate the α-phase crystallites of lamellar morphology and the splitted reflex of α-Fe type (330), HZ- hardened zone, TZ- transition zone to the base metal.

### 3. Conclusion

1. The developed unit for plasma surface hardening of the rail allows conducting a qualitative surface hardening in width, depth and hardness of the surface layer of the metal.

2. The plasma hardening of the side surface of the rail allows one to obtain a favorable structure of the surface hardened layer (mixture of troostite, bainite and martensite) with a hardness of 450-830 HV and a thickness of the quenched layer of 2.5-3 mm. It significantly increases the service life of the rails, due to the 2-3-time reduction in the wear rate of the side surface of the rail.
3. This equipment can be recommended for the further pilot-industrial plasma surface hardening of the rail side surface in the conditions of the East Siberian Railway.

References
[1] Bogdanov V M 1992 Railway Transport 12 30-34
[2] Bataev V A, Bataev A A, Golodkovsky M G, Ostromensky P I and Korotaev B V 2002 The Termites Metals And Metals Processing 12 14-18
[3] Gromov V E 2000 Gradient Structure in the state of the reels of steel [Gradient structural phase state in rail steel] (Moskow: Nedra) p 174
[4] Balanovskiy A E 2017 Welding International 31(6) 467-476
[5] Balanovskii A E 2016 High Temperature 54(5) 627-631
[6] Fedin V M and Borts A I 2009 Metal Science and Heat Treatment 51(11-12) 544-552
[7] GOST RF 51685-2000 Railway rails. General specifications 2001 (Standartinform, Moscow)