Evaluation of the economic feasibility of the introduction of plasma hardening technologies in the Far North enterprises

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Abstract. The various technologies of plasma surface hardening of the crests of wheel pairs with regard to the conditions of the Far North are considered by the example of Norilsk enterprises. When considering economic issues the cost of repairing wheelsets were considered. The advantages and disadvantages of each method of plasma surface hardening are shown. Criteria for the economic feasibility of their implementation are established. It is shown that from the standpoint of hardening process cost of one wheel, it is preferable to use the plasma quenching technology in the arc mode.

1. Introduction

In the repair sector, the “Norilsknickelremont” enterprise covers the entire north of the Krasnoyarsk Territory: Norilsk, Talnakh, Kayerkan, Dudinka, Dikson and Snezhnogorsk. When transporting finished products, JSC MMC Norilsk Nickel (JSC MMC “NN”) uses railway transport therefore the problem of wheelset wear during operation in difficult conditions is also relevant for this enterprise. The railway is distinguished by extreme conditions of operation of the railway tracks and elements of the rolling stock. It is a sharply continental climate with a long period of low temperatures (for negative temperatures it is about 210 days), the minimum temperatures are up to – 60 °C, and the difference of average temperatures during the year is over 70 °C. From the analysis of theoretical and experimental work it follows [1,2] that seasonal fluctuations and extremely low climatic temperatures adversely affect the characteristics of the dynamic strength of machines and equipment made of low carbon and hardened steel, apart from reducing the overall operational reliability of the product. In these conditions, there is a sharp increase in the number of failures of individual units of equipment. However, the substantiation of the increased number of failures and the failure of elements of railway equipment due to contact fatigue damage have not been accumulated so far. The history of the “Norilsktransremont” production association which is the part of “Norilsknickelremont” began on May 18, 1937, when the first train passed through the narrow-gauge railway connecting Norilsk village to the port of Dudinka. And five years later, on April 16, 1942, temporary railway workshops were opened in order to organize the repair of rolling stock. In 1960, the steam engine repair plant was renamed the locomotive car-repair workshop, and in 1980, the rolling stock repair workshop. At the moment, the company specializes in the repair of the rolling stock operated by the Norilsk Railway - dumpcars, gondola cars, platforms, platform-containers, petrol-petrol tanks, hopper-dispensers, railcars, snowplows, platforms “Buran”. Metallurgical plants of the Norilsk industrial region operate slag trucks. In addition, the site carries out
routine repairs of the railway equipment: locomotive carriages, carriage and locomotive wheelsets, inspection of unloading cylinders, restoration of brake shoes.

We have previously analyzed the profitability of creating a unit for repairing wheelsets to serve the needs of the enterprise. To ensure an objective assessment, the following data were considered:

- the need for wheelsets in the repair of freight cars of “Norilsktransremont”;
- the cost structure for the formation of a unit of wheelset in the planned division and third-party organizations;
- a comparison of the expected cost of forming a wheelset and annual costs in the planned amount for the future year when organizing its own unit and when carrying out repairs by third parties [3,4].

On the basis of the enterprise, the repair of wheelsets is carried out by the “Norilsktransremont” production association (“NTR” production association). To date, “NTR” production association performs a limited list of works: preparatory work; surfacing of wheelsets (WS) by the ridge; surfacing wheelsets by the profile of riding; axle boxes pressing-off; check of roller roller; surfacing of axle boxes; replacement of bandages; rough turning; wheel turning; replacement of labyrinths and rings; washing parts and components; coloring. The estimated cost of wheelset formation by “NTR” production association is higher than the cost of: new wheelsets – by 21%; formed wheelsets purchased from third-party organizations – by 45%; formation of waste wheel pairs of the Polar Division of JSC MMC NN by third-party organizations – by 85% [3,4]. The main cost items for wheelsets formation by the “NTR” are: electricity (14%), wage fund and deductions (18%), repair and equipment maintenance (15%), the cost of the wheelset (53%). It can be seen that the main costs are related to the purchase of wheelsets.

At present, statistics on JSC Russian Railways shows that on average the wheel passes between turns about 80 thousand km, which corresponds to approximately one year of operation. Taking into account the fact that during machining aimed at restoring the surface of the rolling profile, about 12 mm of metal is removed, on average the wheel is turned 5 times, and its total estimated operating cycle is 6 years. Due to the surfacing of the ridge, turning of the rolling surface of the wheel to the repair profile occurs with the removal of a smaller volume of metal. At the same time, the deposited metal possesses tribotechnical properties; its wear resistance is 4 times higher than that of wheel steel grade 2. This could increase the service life of the wheel 4 times. All these factors will significantly reduce the life cycle cost of the wheel and the need for new wheelsets from carriers, increase the economic efficiency of transportation. In this paper, an assessment of the possibility of reducing the cost of repairing wheelsets by introducing the technology of plasma surface hardening of the ridges was made.

2. A brief analysis of the work

Traditional methods of heat and chemical-heat treatment of machine parts and tools are intended for volumetric surface treatment and do not allow local processing of rapidly wearing areas [5-10]. Modern technologies of surface hardening of metals and alloys with the use of a concentrated energy flux (CEF), laser beam [5,6], electron beam [7], plasma arc [8,9] are characterized by high heating and cooling rates, short duration and local effects on metal. The main aim of the use of new hardening technologies, based on concentrated energy fluxes (CEFs), is to increase the strength, wear and corrosion resistance [5,7,10,11]. From the works [12,13] it is known that the most effective method of increasing the durability of tires and reducing purchased wheelsets, in which the wear of the ridge is significantly ahead of the growth of rolled metal, is plasma hardening [14,15], surfacing of worn flanges of wheelsets of electric locomotives with subsequent hardening [16,17]. This method has indisputable advantages in comparison with restoring by turning and forming a profile configuration by reducing the thickness of the bandage. Surfacing of the ridge in combination with the shape of the covering profile minimizes the technological wear of the bandage prior to writing off, mainly determined by its natural wear. Simple locomotives are eliminated, caused by the need for intermediate turning (for an electric locomotive of 8-12 h); reduced costs of maintaining machines for turning without rolling out and the purchase of cutting carbide tools; salary savings are achieved [18,19]. Our brief analysis of individual works on plasma hardening made by various authors [12,13,20-24] showed that in most cases, they are aimed at solving the narrow technological task of hardening (increasing hardness) of a particular steel grade
[21,22], from which one or another part is made. In addition, most of the work in the field of plasma hardening of metals was performed on various equipment [15,18,19,23,24]. This has fundamental structural and technological features (plasma torch with interelectrode inserts, with a porous anode [22,23], with different plasma-forming gases and media [10,12,25,26], in various technological modes (jet or arc (direct or reverse polarity), three-phase arc, vacuum arc, etc.) [26,27], performance method (with magnetic or mechanical expansion of the jet (arc), creeping or reflected laser jet, etc.). Based on the analysis of the work, the technical and economic parameters of various hardening methods applied to wheelsets of rolling stock were formulated. Table 1. The above information shows the competitiveness of the technology of plasma surface hardening of metals and alloys. In fact, there are two methods implemented now in rail transport of Russian Railways: plasma surface hardening technology of the ridges of wheel pairs in the plasma mode arc [16] and in the plasma jet mode [28,29].

Table 1. Technical and economic parameters of CEF hardening methods of medium carbon steels (steel 40, 45, 55). Sources of information [5-22].

| Parameter | Plasma ark | Beam | laser | electronic |
|-----------|------------|------|-------|------------|
| 1         | 2          | 3    | 4     |             |
| Structure of the hardened layer | M^a-T^b-C^c-F^d-P^e - R^f_A | M^a-T^b-C^c-F^d-P^e - R^f_A | M^a-T^b-C^c-F^d-P^e - R^f_A |
| Hardening depth, mm | 1.5–4 [38] | 1.5–1.8 [5,6] | 1.5–5 [4,32] |
| The hardness of the hardened layer, MPA | 7 200 | 7 400 | 7 400 |
| Hardness stability in width and depth | High | High | High |
| Effective heating efficiency | 0.65–0.75 | 0.15–0.35 | 0.85–0.90 |
| Capital expenditures on equipment, US million dollars | 0.05–0.1 | 0.8–1.9 | 1.3–2.8 |
| Current costs for 1 lin m, USA $ | 1–3 | 5–8 | 7–10 |
| Worker qualifications | Medium | High | High |
| Biological and radiation safety | No | Yes | Yes |
| Production culture in places of introduction | Medium | High | High |

^aM-martensite, ^bT-troostite, ^cC-sorbitol, ^dF-ferrite, ^eP-perlite, ^fR_A-residual austenite.

3. Comparative evaluation of plasma hardening methods of locomotives wheelsets ridges

For a comparative assessment, we analyzed the technological features of the technologies [16,29] using, also, the regulatory documents of Russian Railways, in which there are economic parameters of plasma hardening per one wheelset. From the point of view of increasing the wear resistance of the wheelset, then these two technologies (Figure 1) provide equivalent parameters in hardness and depth of the hardened layer, since these output values that are strictly defined by the regulatory documents of JSC “Russian Railways”. From the standpoint of instrumental support for the implementation of this technological operation of wheelset ridges surface hardening, there are differences in equipment (main and auxiliary ones).

Plasma hardening methods of ridges of locomotives wheelsets (Figure 1), b, is intended for obtaining a hardened wear-resistant layer in the surface layer of the wheelset tire. Installation is delivered in three types of modification: – sub-rail installation; – rolled wheelsets hardening; – installation on automated wheel-turning lathes of the rail type (machine-tool one). In the case of the rail version, an installation pit of a certain shape is required for installation. The installation is different from analogs (Table 2): there is no water cooling of the plasma torches; compressed air with a pressure of 6-8 kg/cm² is used as a cooling and plasma-forming gas. As a technological source of plasma current, typical air-plasma
cutting systems of the Russian manufacturers are used; operations that directly affect the quality of hardening are fully automated.

![Image](a) ![Image](b)

**Figure 1.** The appearance of the installations of wheelsets ridges plasma surface hardening at jet mode (a) and at plasma arc mode (b).

| No. | Main parameters | Values |
|-----|-----------------|--------|
| 1   | Power supply - AC supply: | |
| 2   | - supply voltage, V | 380 |
| 3   | - frequency Hz | 50 |
| 4   | - power consumption at nominal operation mode, not more than kW | 15 |
| 5   | Output current, A | 20-160 |
| 6   | Idling voltage, V | 275 |
| 7   | Output voltage, V | 145 |
| 8   | Efficiency, % | 85 |
| 9   | Weight of power supply unit, kg | 60 |
| 10  | Overall dimensions of the power supply (LxWxH), mm | 670x330x630 |
| 11  | Compressed air consumption, m³/h | 36 |
| 12  | Weight of burner with cable hose, kg | 4.8 |
| 13  | Length of cable hose, m | 9 |
| 14  | The depth of the hardened layer: | |
|     | - minimum, mm | 1.5 |
|     | - maximum, mm | 3.5 |
| 15  | Hardened layer width: | |
|     | - minimum, mm | 8 |
|     | - maximum, mm | 60 |
| 16  | Duration of starting, % | 100 |
| 17  | Time of hardening of one wheelsets tire, min | 14 |
| 18  | Type of modification | For rolled wheel sets |

The installation of Figure 1a includes a device for plasma processing, including a plasma torch and a flow transducer, designed to produce low-temperature plasma and evenly distribute it over the processed surface. The plasma torch is included in the work after its installation in the working position above the processed surface and imparting the last desired motion speed. Technical characteristics of the installation (Figure 1a) are presented in Table 3.
### Table 3. Main technical characteristics of plasma quenching at plasma jet mode.

| Characteristic                                | Value   |
|-----------------------------------------------|---------|
| Installed power                               | kВА 120|
| Power consumption                             | kW 90   |
| Nitrogen consumption                          | g/s 3...5|
| Working pressure of nitrogen in the gas line  | ATMG 2...5|
| Type of plasma generators cooling             | Forced water |
| Cooling water consumption                     | kg/s 0.8|
| Water working inlet pressure of the cooling elements | ATMG 3...4|
| Linear rolling speed of the wheel surface     | mm/min 100...500|
| Performance                                   | PI/shift up to 30|
| Installation area                             | m² ≈40|

Power sources on installation (Figure 1a) are made on the basis of serial rectifier thyristor units (TP4-500/230N-I-UHL-4) with the introduction of changes and supplements to the design and circuit. Each power source contains: a 3-phase rectifier bridge supplying the working arc of the plasma torch; power input panel; power source auxiliary arc plasma torch; instrument panel; automatic power switches of the pulse-phase control system (PPCS), air coolers and elements of the control system located in the power sources; devices for measuring output current and voltage of the power source rectifier bridge; circuit breakers; ohmic divider to measure the voltage between the electrodes of the plasma torch; light elements of the power supply status; oscillator. Three-phase dry transformers with housings, type TS3-100/0, 66-UKHL4 are used as batteries for the working arc of plasma torches. They are intended for matching voltages and galvanic separation of the supply mains and plasma torches. The gas supply system is designed to provide a plasma-forming gas with a given flow rate into the plasma torch duct. The system includes a balloon ramp consisting of 10 containers of eight 40-liter cylinders, two manifolds and two gearboxes, as well as regulating needle valves with manual and electric drives, diaphragm gate valves with electromagnetic drive, pressure stabilizing filters, measuring sections, measuring sensors and devices. The electric pump unit is the main component of the water supply system and provides cooling of the assemblies and ducts of the plasma torches, which are exposed to heat effects from the electric arc and plasma during operation. In installations with a closed cooling system, water is taken from the water supply tank and, after passing through the cooling duct, is drained back into it. The volume of the reserve tank, in this case, is determined on the basis of the number of wheelsets processed per day with a natural heat removal. In case of a small volume of the water storage tank and the intensive operation of input distribution device, the installation of coolers is required.

For operation with the installation shown in Figure 1, the following engineering support is required:

1. Electricity. Supply of electric power of 120 kVA to the input distribution device (copper cable is 4×95 mm², voltage ~ 380 V).
2. Water supply and sewage. To cool the plasma torches, drinking or process water with a metal salt content not exceeding the drinking water norm, with a flow rate of 0.8 kg/s and a pressure of 0.2 ÷ 0.4 MPa, is used. Water tanks and water ducts should not freeze. Water consumption per wheelset does not exceed 0.7 m³. Drain is free-flow with a water temperature of not more than 60 °C without changing the quality of the source water. A variant with a closed cooling system with water storage tanks with a capacity of ≥10 m³ is acceptable.
3. Ventilation and heating. The air temperature in the premises of the installation (control room ≈ 12 m², electrical equipment ≈12m² and water storage tanks ≈ 12 m³) in the cold season should be comfortable for the work of the operating personnel (operators).
4. Air supply. Compressed air with a pressure of 0.6 MPa is for technological purposes (purging cooling ducts, purging the gas duct of plasma torches, etc.). Air consumption is no more than 5 m³/h (as required).
5. Nitrogen supply. Nitrogen is of high purity of the 2nd grade in accordance with GOST 9293-74 [30] (99.95%) from a balloon ramp or ducted. Balloon ramp has 80 and 40-liter cylinders (10 containers...
of 8 cylinders) at a pressure of 15 MPa. Transportation of nitrogen from the ramp to the central control panel and from the console to the plasma torches is performed through pipe 15 at a pressure of 0.7 MPa. The ramp should be placed in a room of ≈ 12 m², protecting cylinders and gearboxes from precipitation. The room must have an access road and a lifting device for unloading and loading containers with cylinders from the car into the room and back. The weight of one container with cylinders filled with gas (8 pcs.) ~ 800 kg. Nitrogen consumption ~ 3 m³ per one wheel set. It is possible to place the nitrogen ramp behind the fence in the workshop with the possibility to load/unload the balloon containers with the use of a crane. Instead of a balloon ramp, a nitrogen generating unit can be used.

The above description of the instrumental support of installations shows significant differences in the technical implementation of the plasma hardening technology, which consists in the complexity of the equipment used during plasma quenching at jet mode (Figure 1a). As applied to the conditions of the Extreme North, the use of water cooling at the facility (Figure 1a) increases the risk of equipment failure due to an emergency situation. Even a simple comparison of power consumption in a plasma jet mode of 120 kW and in a plasma arc mode of 15 kW shows the advantage of the latter method since this will affect the cost of the hardening process. Indeed, analyzing the regulatory documents of Russian Railways, we see that the cost of hardening one wheelset using plasma quenching at jet mode (Figure 1a) is 5,800 rubles. The cost of hardening one wheelset using plasma quenching at arc mode (Figure 1b) is 1,200 rubles.

4. Conclusion

On the basis of the data presented above, the following conclusion can be made: of the considered variants of wheelset plasma surface hardening technology, the most economically viable technology is plasma quenching at air-cooled arc mode, Figure 1b. Our earlier calculation of the cost of repairing wheelsets of the “Norilsktransremont” production association [3,4] indicates that an additional increase in prime cost is possible in a limited range of costs, provided that the overhaul life increases substantially. Considering this economic factor with equal wear resistance indicators of the considered technologies of plasma surface hardening of wheelsets, the prime cost of the hardening process itself comes to the fore. It is obvious that the prime cost of plasma hardening at plasma jet mode in the amount of 5,800 rubles is critical for the “Norilsktransremont” production association, because it exceeds the current prime cost of repair. In case of molding of wheelsets with the use of plasma quenching technology at jet mode by “Norilsktransremont” production association, the repair costs will increase by 24 million rubles compared to the current situation (80%). In case of molding of wheelsets with the use of plasma quenching in arc mode, the repair costs will increase by 4 million rubles compared to the current situation (10%).

Thus, for JSC “GMK” NN”, the most economically feasible variant is the formation of wheelsets on its own using new technologies of plasma surface hardening of wheelsets ridges, considering the provisions presented above. At the same time, the reduction in the cost of wheelsets repair (as compared to the planned costs for the purchasing molded wheelsets) will be determined in the type of plasma hardening technology used.

References
[1] Balanovsky A E, Shtayger M G, Grechneva M V, Kondrat’Ev V V, Karlina A I 2018 IOP Conf. Ser.: Mater. Sci. Eng. 411(1) 012012
[2] Khomenko A P, Gozbenko V E, Kargapoltsve S K, Minaev N V, Karlina A I 2017 Int. J. of Appl. Eng. Res. 12(23) 13773-13778
[3] Shchadov I M, Chemezov A V, Konyukhov V Yu, Beliaevskia T S 2015 Bulletin of ISTU 5(100) 297-300
[4] Chemezov A V, Konuyxov V U, Zimina T I Modern Technologies, System Analysis. Modeling 2017 1(53) 195-200
[5] Engel S L 1981 Source Book on Applications of the Laser in Metalworking p 149
[6] Komanduri R, Hou Z B 2001 Int. J. of Heat and Mass Transfer 44(15) 2845-2862
Bataev I A, Golkovskii M G, Losinskaya A A, Bataev A A, Popelyukh A I, Hassel T, Golovin D D 2014 Appl. Surface Sci. 322 6-14
Klein A N, Cardoso R P, Pavanati H C, Binder C, Maliska A M, Hammes G, Fusao D, Muzart J L 2013 Plasma Sci. and Techn. 15(1) 70-81
Balanovsky A E, Shtayger M G, Kondrat'Ev V V, Van Huy V, Karlina A I 2018 IOP Conf. Ser.: Mater. Sci. Eng. 411(1) 012013
Balanovsky A E, Shtayger M G, Kondrat'Ev V V, Nebogin S A, Karlina A I 2018 IOP Conf. Ser.: Mater. Sci. Eng. 411(1) 012014
Balanovsky A E, Grechneva M V, Van Huy V, Ponomarev B B 2018 IOP Conf. Ser.: Mater. Sci. Eng. 327(4) 042010
Balanovskii A E, Grechneva M V, Huy V V, Zhuravlev D A 2017 IOP Conf. Ser.: Earth Environ. Sci. 87(9) 092003
Balanovskii A E, Grechneva M V, Huy V V, Zhuravlev D A 2017 IOP Conf. Ser.: Earth Environ. Science 87(9) 092004
Balanovskii A E, Huy V V 2017 Letters on Mater. 7(2) 175-179
Balanovskii A E, Huy V V 2018 J. of Friction and Wear 39(4) 311-318
Medvedev S I, Nezhivlyak A E, Grechneva M V, Balanovsky A E, Ivakin V L 2015 Welding Int. 29(8) 643-649
Ivanchik N N, Balanovsky A E, Shtayger M G, Sysoev I A, Karlina A I 2018 IOP Conf. Ser.: Mater. Sci. Eng. 411(1) 012035
Balanovskii A E 2018 High Temperature 56(4) 486-495
Balanovskii A E 2018 High Temperature 56(3) 319-326
Balanovskii A E 2018 High Temperature 56(1) 1-9
Wagiman A, et al. 2015 Applied Mechanics and Mater. 699 105-110
Bourithis E, Tazedakis A, Papadimitriou G 2002 J. of Mater. Proc. Techn. 128 169-17
Balanovsky A E 2017 Welding Int. 31(6) 467-476
Balanovsky A E 2016 High Temperature 54(5) 627-631
Ivanov N A, Balanovskii A E, Kalashnikov Y D, Ryazantsev V V, Skripnichenko A S 2016 High Temper. 54(2) 289-293
Kondrat’ev V V, Balanovskii A E, Ivanov N A, Ershov V A, Kornjakov M V 2014 Metallurgist 58(5-6) 377-387
Balanovskij A E 1993 Teplofizika Vysokikh Temperatur 31(2) 328-330
Balanovskii A E 1993 Welding Int. 7(12) 967-970
Balanovskij A E, Nesterenko N A 1992 Teplofizika Vysokikh Temperatur 30(5) 1029-1031
GOST RF 9293-74 Nitrogen nitrogen and liquid. Technical conditions. 1976 (Standartinform, Moscow)