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PLASMA HIGH-SPEED SURFACE HARDENING OF WHEELSETS

Petrov S.V

Abstract

Wear of wheels and rails is a complex process, depending upon many factors, which are interrelated in the quantitative respect.

Method of plasma surface hardening is among the cheapest and most efficient methods used at repair enterprises to increase wear resistance of roll surfaces, including the flange.

This work was aimed at development of a technology and equipment for plasma surface hardening to provide an increase in contact-fatigue strength of metal and, as a result, an increase in service life of the wheelsets.

Heat hardening of steel parts is one of the most efficient methods of increasing service life of heavy-loaded machine and mechanism parts and decreasing their material consumption. Local heat treatment is justifiable in many cases in terms of technology and cost effectiveness, where only the most loaded working surface of a part is subjected to hardening, while the bulk of a material remains untreated. Thermal high-frequency and plasma-gas treatment of parts was widely used in industry as a method of surface hardening. Further progress in the improvement of the quality of heat treatment of working surfaces is related to the use of concentrated energy sources: electron and laser beams and plasma jet. They will provide the improved quality of hardening and service characteristics of parts, such as strength and wear resistance. Among the methods of heat treatment involving the highly concentrated heat sources, the plasma method has the highest efficiency and capacity. It is characterized by reduced costs, affordability of the process equipment and larger sizes of the hardened zone.

INTRODUCTION

Processes developed by the authors, which involve the use of plasma of the products of combustion of air with a fuel hydrocarbon gas, take a special place among other plasma processes for materials treatment. Owing to a number of unique properties of this plasma, such as high heat capacity and thermal conductivity, high controllability of oxidation-reduction potential, availability and relatively low cost, the processes on its base are of an increasing interest for research and industry.

Cost effectiveness and technical expediency of using air-gas mixtures become particularly appreciable with an increase in the power of a plasmatron and transition to supersonic velocities, where the optimal conditions shift towards the range of the high plasma gas flow rates. Comprehensive investigations (both experimental and those based on mathematical models) yielded the relationships between principles of building the electric-arc equipment peculiarities of the processes of generating the combustion products plasma, its interaction with materials and the final technological result.

COMBUSTION PRODUCTS PLASMA AND ITS PROPERTIES

To provide the required parameters of the atmospheres is an indispensable condition for making the plasma treatment processes as effective as possible. Oxidation-reduction and transporting properties of the combustion products plasma are determined by its composition.

Analysis of variations in a composition of the air-gas plasma depending upon the temperature shows that a CO_2 molecule has the lowest stability. It is characterized by the earliest and most complete dissociation occurring during heating. The next to dissociate is H_2O. At a temperature above 4000 K both CO_2 and H_2O are almost absent.

Molecular hydrogen H_2 is present in a large amount (15 vol.% at a $\alpha = 0.6$) in a rich mixture also at a $\alpha \cong 1$ at a temperature of up to 5000 K as a result of dissociation of water. Variation in the concentrations of the combustion products with temperature is most intensive at 3500 K. The CO molecule is stable, and it is present in the plasma at a temperature of up to 8500 K. Atomic hydrogen and oxygen are formed in heating to a temperature above 2500 K, while nitrogen is formed at a temperature of more than 4500K. Equilibrium carbon (in the gas phase) is formed at a temperature of more than 5500 K due to dissociation of CO, reaching a maximum content of 4-5 % at 8500 K. An increase in temperature over 7000 K is accompanied by a substantial increase in the concentration of an electron gas. For example, at 9000 K it is 1 vol.% and at 12000 K it amounts to 12 vol.%. At the same time, the concentration of positive singly charged ions N^+, C^+, H^+ and O^+ grows as well.

Negative singly charged ions O^-, N^-, H^- and $C^-$are also formed in the combustion products plasma. Their highest content equal to 10^{-3} vol.% is found in a temperature range of $(10\text{-}14)\cdot10^3$ K. In a temperature range of up to 20,000 K the second-order ionization is still insignificant. Thus, at 20,000 K the content of O^{2+} is no more than $1.5\cdot10^{-3}$ vol.%.

We should note a peculiarity of the ion state of the combustion products plasma in a temperature range of $(9\text{-}13)\cdot10^3$ K, where carbon makes a substantial contribution to the ionic current transfer.

At $T = (4\text{-}7)\cdot10^3$ K the plasma contains mostly nitrogen and carbon monoxide in a molecular form, the oscillation temperature of which can be easily "frozen" during expansion of the plasma. Oxygen and hydrogen are in the atomic state. Therefore, they can actively interact with a material treated. For example, at T = 4000 K and a $\alpha = 0.6$ the content of atomic oxygen is approximately 9 %. At a $\alpha = 1$ the content of atomic hydrogen is approximately 20 %, that of carbon monoxide is 7 % and that of oxygen is 15 %.

Values of the specific energy inputs during plasma hardening of the majority of materials amount to 5-10 kW h/m^3. According to the upper limit of the specific energy (10 kW h/m^3), the mean mass temperature of the plasma jet is approximately 6500 K and that of the constricted arc is approximately 12,000 K.

Plasma of the products of combustion of CH_4 has a sufficiently high heat content. At a power take-off of 1 kW h/m^3, its temperature decreases only by 200 K within a range of both relatively high temperatures, i.e. 8000-6000 K, and relatively low temperatures, i.e. 4000-3000 K. Owing to chemical reactions, thermal conductivity of the combustion products plasma is much higher than thermal conductivity of the "frozen" mixture.

The characteristic feature of generation of the electric-arc plasma is that the discharge burns in a channel of the plasmatron in strong radiation and sound fields. The level of the sound pressure in the plasmatron is rather high and amounts to 140 db. The sound is excited by turbulent pulsations of the plasma flow.

The zone of disturbance of the local thermal equilibrium (LTE) is formed in a region where a cold multiatomic gas is introduced into the ionized columns of the arc plasma. In the case of using molecular gases, the difference between the electron and oscillation temperatures and the translation and rotation temperatures can be several thousands of degrees.

In such a case, in a local region of the plasma flow the possibility exists of reversing the effect of the second (volumetric) viscosity, i.e. it can lead to amplification of the sound, rather than toits attenuation. The oscillation-translation non-equilibrium of $T_K > T$ with propagation of the sound waves becomes a source of the energy which is transferred to the wave during the thermal deactivation process.

At a sufficient difference between the oscillation T_K and translation T temperatures, the second viscosity can become negative and cause an increase in the acoustic disturbances.

The relaxation viscosity ξ can significantly exceed (e.g.by two orders of magnitude at a temperature of several thousands of degrees) the shear viscosity η.

Formation of the negative (reversed) viscosity in an oscillating non-equilibrium gas leads to instability and other effects that have no analogues in an equilibrium gas.

In the molecular oscillating non equilibrium gas, the intensity of the acoustic field can exceed the intensity of this field induced by a natural turbulence. The effective amplification of sound due to reversal of the effect of the relaxation viscosity occurs at frequencies of 10^4 -10^5 Hz.

It can be suggested that an increase in the intensity of the acoustic field in a non-equilibrium environment (as compared with the equilibrium one) is equivalent to the effect of an external sound source. Therefore, an amplified sound in the non-equilibrium region of the environment can affect the natural turbulence. In addition, downstream in the region where gas can be regarded as the equilibrium one and where the relaxation viscosity is positive and high, there should be an intensive absorption of the energy of an "excessive" acoustic field. These effects can have a marked influence on parameters of the plasma flow, providing that the non-equilibrium energy of molecular oscillations, which is transformed into the energy of the amplified acoustic wave followed by its dissipation, is comparable with the total energy of the plasma.

INTERACTION BETWEEN PLASMA AND SURFACE

It can be suggested on the basis of analysis that the combustion products plasma is more power-intensive than plasma of any biatomic gases. Heat transfer from the combustion products plasma to a work piece heated increases both owing to a high temperature level and owing to a change in transporting properties of the dissociated combustion products (due to their subsequent recombination). Therefore, the arc plasmatrons operating with an air-gas mixture are indicated for intensive local heating and melting of small surfaces, as are the cases of high-speed hardening, cutting or alloying of steels, glazing of building materials, spheroidization of powders, heating of metal edges, etc. Parameters of surface heating were determined through solving the equation of non-stationary thermal conductivity with the appropriate boundary conditions. Dependence of the depth of heating to T = 850 C upon the heat transfer coefficient can be approximated by the following relationship:

$$\delta_h = 1{,}73\cdot10^5\ [(T_{ef} - T_{av})^{-1{,}44}/\alpha],\ \text{mm}$$

where T_{ef} is the averaged temperature of the heating medium, K; T_{av} is the averaged temperature of the work piece heated, K, in the layer with a thickness of δ_h, mm; and α is the heat transfer coefficient, W/m deg.

The relative travel speed can be approximated by the following expression:

$$W = 4{,}28\cdot10^{-9}\ l_h\ (T_{ef} - T_{av})^{0{,}46}\cdot\alpha^2,\ \text{m/s}$$

where l_h is the length of the heating zone, m. Accuracy of the formulae given is ± 10 %.

Optimization of the process of surface plasma hardening was done using the modern computer facilities. Solution of this problem is associated with the possibility of reliably predicting the material structure through selecting the thermal effect parameters. Optimization of the technology is reduced to making special arrangements in order to produce the preset configuration of the plasma flow and to choosing the required conditions of the hardening process, predicting the structures formed and residual stresses induced. The entire work on the development of software was broken into three interrelated and, at the same time, sufficiently independent stages. The problem of calculation of thermal cycles for an arbitrary microvolume within the region treated for the preset type of a material was solved at the first stage.

The second stage of the work was associated with the development of software for modelling the processes of structural transformations, as well as physical and chemical transformation taking place in a material investigated under substantially non-equilibrium conditions of rapid heating and cooling, based on the currently available fundamental concepts of the processes under consideration. The tasks of the third stage of the software development involve construction of the correlation models of the "material structure - physical-mechanical properties" type.

PLASMA EQUIPMENT FOR SURFACE HARDENING

Based on the above-described ideology, the has developed and mastered the manufacture of a number of new types of plasma equipment to realize its new technologies. The surface plasma hardening technology is characterized by new capabilities for increasing contact-fatigue strength of metal and, as a result, improving reliability of the wheelsets of the rolling and traction stock. Commercial application of the technology for plasma surface hardening of the wheel necks is done using the 'Topas-4' machine. It is based on the two-module design and includes:

- power supply, control panel (Fig.1);

Fig.1. Power supply, control panel

- two plasma modules (Fig.2) with plasmatrons (Fig.3);

Fig.2. Plasma modules

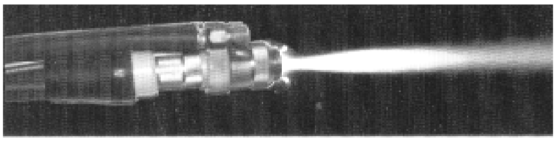

Fig.3. Plasmatron

- Semi-automatic process line (Fig.4).

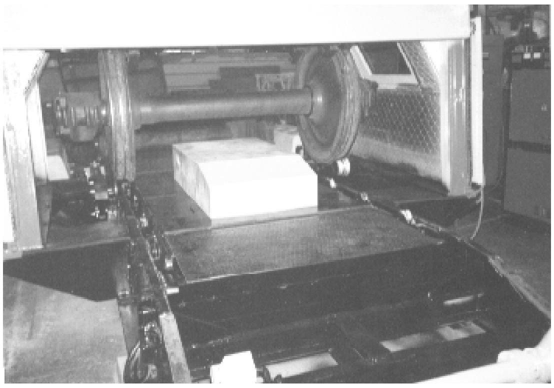

Fig.4. Semi-automatic process line

The machine provides:

- oscillation ignition of the plasmatrons, turning on power, control of current and arc voltage, internal diagnostics of the power supply system;

- alternate turning on of the first and second plasmatrons from one power supply;
- switching on, control and regulation of flow rate of the plasma gas;
- switching on, control and regulation of flow rate of the combustible hydrocarbon gas (methane, propane-butane);
- feed of water to cool the plasmatrons, interlocking and indications;
- automatic turning on of the operating conditions and their automatic turning off upon the end of the hardening cycle.

Specifications of the machine for plasma surface hardening of the wheel necks are as follows:

Power, kW	20-80
Plasma gas mixture flow rate, $m^3 h^{-1}$	4-10
Natural gas content of the air mixture, %	5-15
Cooling water consumption, $m^3 h^{-1}$	1
Speed of hardening, cm/s	1-2
Depth of the hardened layer, mm	0.5-3.5
Width of the hardened path mirror, mm	25-35

It is advisable to harden the wheelsets using an automatic production line (Fig.4). Such a line can be established, requiring no major construction operations, in the gap in the rail track. Here, the entire cycle, beginning with feeding a wheelset, its mounting on a rotator in a noise-proof box, hardening and unloading into a collector is done automatically. The process is monitored and controlled from a control panel.

Plasma surface hardening is a complex multifactorial process. The automatic line prevents operator mistakes. The process line includes:

1) Plasma hardening equipment UVPZ-2M:

- power supply	1 pc.
- control devices	1 set
- plasma modules	2 sets

If necessary, the equipment can be additionally fitted with a unit for independent cooling with closed-loop water feed.

2) Semi-automatic line for process control:

- noise- and radiation-proof chamber	1 set
- device for transportation of the wheelsets (completed with components for the unified system of wagon braking equipment)	1 set
- control equipment	1 set

The process line for hardening the wheelsets requires no extra capital investments for construction operations, can be readily added to the repair lines of car sheds or factories manufacturing the wheelsets and can be used to harden all types of passenger, cargo and motor car wheels.

Specifications:

Conveyer speed, $m\ min^{-1}$	8.2
Wheelset rotation speed, $m\ s^{-1}$	0.84
Installed capacity, kVA	105
Mains voltage, three-phase AC, 50 Hz, V	380
Flow rate of compressed air under mains pressure of 0.5-0.6 MPa, $m^3 h^{-1}$	5-8
Flow rate of fuel gas, $m^3 h^{-1}$:	
- methane	0.5
- propane-butane	0.2
Consumption of cooling water under mains pressure of 0.3 MPa, $m^3 h^{-1}$	1.5
Dimensions, mm:	
- length	6650
- width	3470
- height	3600

THE TECHNOLOGY OF PLASMA SURFACE HARDENING

The technology of plasma surface hardening is characterized by new capabilities in terms of increasing contact-fatigue strength and, therefore, increasing reliability of traction for wheelsets. Intensity of wear of the wheelset flanges after plasma hardening is much lower than that of the traditionally treated ones (2.5-3 times). The technology have developed for hardening of the wheelsets has two peculiar features: 1. local (within the zone of the highest wear) surface hardening of the wheel flange (Fig.5) to a depth of 2.5-3 mm and width of 35 mm, ensuring an increase in hardness from 280 HB (in the base metal) to 450 HB. This provides an optimal relationship in hardness of the wheel and rail surfaces in contact; 2) change in structure of the hardened wheel zone from a ferrite-pearlite mixture with initial grain size of 30-40 μm to a mixture of fine-acicular or structureless martensite with a rosette-type troostite in a ratio of 50:50 %. This produces improvement of mechanical properties (including decrease in friction coefficient in contact of the ridge and the side surface of the rail) and increase in crack resistance of the wheel material within the plasma hardening zone.

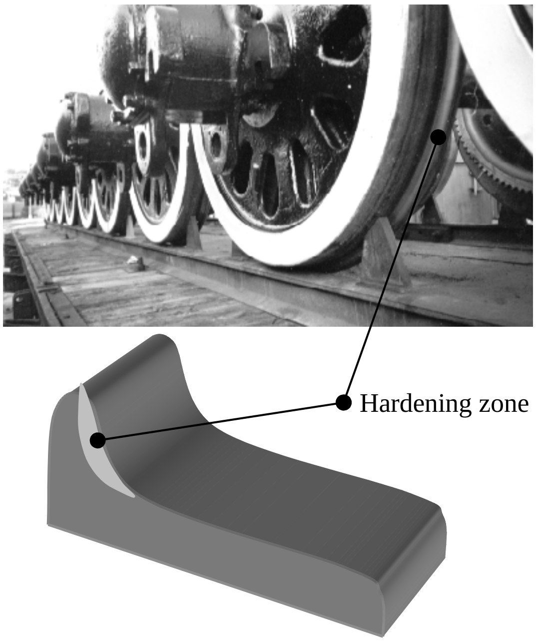

Fig.5. local surface hardening of the wheel flange

Our investigations and experience of operation of the plasma hardening machines prove that this process can be automated. All the above three problems are reduced to ensuring repeatability of the optimal thermal cycle for each wheel. For this we created the off-line optimization system.

Proceeding from a requirement of the guaranteed accuracy and repeatability of the hardening process, developed the computerized off-line optimization system for the UVPZ-2M machines. The off-line optimization system provides:

- in-process programming of working conditions and parameters;
- real-time display of the state of the process parametersbeing monitored;
- recording and permanent memory storing of parameters of the technological process of plasma surface hardening of wheelsets;
- output of the stored information to PC;
- processing of analogue signals from the "TOPAS-Smotrich" pyrometer, power supplies of the "Plasma-2" plasmatrons and pressure transducers, as well as of input discrete signals from the final control mechanisms,
- formation of output control instructions following the preset program.

Optimization of the technology involves special precautions to produce the preset configuration of the plasma flow and the proper selection of required conditions of the hardening process. Reliable prediction of structures and residual stresses formed in the hardened layer can be made only in the case of using a non-linear mathematical model. Allowance for non-linearity of thermal-physical parameters of the plasma and material treated makes it possible to determine local extreme of rates of variations in temperature of certain micro-volumes within certain time intervals.

Hardness of the surface layer of metal of wheels is increased due to cold working during movement from 285 HB to 350 HB, while on flats formed in braking with blocked wheels the hardness value may amount to 50-55 HRC.

In this situation tempering of the surface layer of metal prior to re-profiling the roll surface of wheels make the work of cutting tools and a lathe much easier. This enables the rate of turning to be increased and a substantial saving to be achieved.

INDUSTRIAL TESTS

First locomotives with the wheels plasma hardened were put into experimental operation at the Lviv-Zapad shed early in March 1996 and the cars - at the Kyiv-Passenger shed in summer that same year. Comparison of the plasma hardened wheel ridges of electric locomotives with the traditional ones under the same service conditions of the Lviv railway proved already by the end of April 1996 the expected two-fold decrease in the rate of their wear. After that a decision was made to expand the scopes of application of plasma hardening of the wheelset ridges. It was for that purpose that the new specialized two-module high-speed plasma hardening machine UVPZ-2M was developed. Its application initiated the arrangement of workshops for plasma hardening of wheelsets without wheeling out from under a locomotive, which was completed in 1997. This was done using the KZh-20 machine tool at the Znamenka shed. Similar workshops for plasma hardening with wheeling out were arranged in Osnova, Kharkiv. Workshops for plasma hardening of the wheelset ridges without wheeling out, based on the KZh-20 machine tool, were built at the Kazatin shed, those based on the K-40 machine tool were built at the
Lviv-Zapad, Osnova (Kharkiv), Kotovsk, Nizhnedneprovsky junction, etc. The car wheels are hardened using the specialized production line with wheeling out at Kyiv, Kherson, Dneprodzerzhinsk and other car sheds.

The final outcome of more than 6 years operation of locomotives and cars with the plasma hardened wheelset flanges is as follows: 1. Plasma hardening is a highly productive efficient method for 2- or 3-fold extension of service life of the wheelsets, which can be applied under conditions of a typical car shed. The accepted technology provides a very high safety factor for operational reliability of the wheelsets. 2. The guaranteed reproducibility of the best indicators of operational reliability and wear resistance is ensured by keeping precisely to the prescribed hardening parameters for every wheel.

CONCLUSIONS

1. The readily available high-enthalpy reactive air-gas plasma is widely applied as the plasma-forming environment for technology purposes.
2. The new approach to making the plasma surface hardening machines is presented. The new types of the plasma hardware were developed and the new technological processes of high-speed plasma surface hardening were devised.
3. The process was developed and the specialized equipment was manufactured for plasma surface hardening of wheelsets.
4. The equipment provides a hardened layer depth of 2-3 mm and a hardened path width of 25-35 mm at a hardening rate of 1.5-2 cm s^{-1}.
5. Hardness of the treated layer can be regulated within wide ranges (300-700 HB). The layer has a finely dispersed structure.
6. The equipment is characterized by new capabilities for increasing the contact-fatigue strength of metal and, hence, improving the reliability and increasing the service life of the wheelsets.
7. Intensity of wear of the plasma hardened wheel flanges is much lower than that of the mass-produced ones (2.5-3 times).