PLASMA EQUIPMENT and TECHNOLOGIES for HARDENING and REPAIR of WHEELSETS

Petrov S.V.

Abstract.
The work solves the package of problems associated with hardening and repair of wheelsets. Plasma equipment and technologies have been developed and tested. They meet contradictory requirements to different zones of a wheel during its life time. These are two methods which provide a constant shape of the wheel flanges, i.e. plasma surface hardening and deposition of wear-resistant coatings, plus tempering of the surface layer of increased hardness prior to re-profiling. All the three processes are applied using the UVPZ-2M machine.

1. Introduction

Local heat treatment is justifiable in many cases in terms of technology and cost effectiveness, where only the most loaded working surface is subjected to hardening, while the bulk of a material remains untreated. Plasma surface hardening allows wear to be decreased and service life of heavy-loaded machine parts to be extended 2-5 times. The novel method of plasma hardening is technically and economically preferable for heat treatment of a large number of parts. One example of its application is high-speed surface hardening of all types of passenger, freight and locomotive train wheelsets. Tests show that in all cases the amount of wear of the wheelset ridges after plasma hardening is much lower (2.5-3.0 times) than that of the ridges after standard heat treatment. The new approach to making machines for high-speed plasma surface hardening has been developed based on utilization of the variable-composition mixture of gas and air and the stabilized elongated electric arc that burns in a plasmatron and is adapted to meet the technology requirements.

2 Modelling of the plasma hardening process

The key task of the mathematical support realized in the form of the specialized software package based on modern computer facilities is to optimize the hardening process through selection of such heating-cooling conditions which would provide the desirable strength properties for a given material (steel grade) within the preset space area of heat treatment.

Fulfilment of this task is associated with a possibility of having a reliable prediction of the material structure to be produced, based on the selected thermal effect parameters. Considering complexity of the latter, the total work on development of the software was divided into three inter-related and, at the same time, sufficiently independent stages.

Stage 1 involved solution of the problem associated with computation of thermal cycles for an arbitrary micro-volume within the treatment area for the preset type of a material (density of a material, as well as temperature dependence of thermal conductivity and specific heat are considered to be known). External effects which can vary over a wide range include consumption, initial temperature and thermal-physical properties of the plasma, size of the zone to be heated, character of relative displacement, speed of displacement of the material treated, degree of preheating-cooling, cooling conditions upon leaving the plasma treatment zone, etc.

It should noted, however, that the latter approach is associated with a large scope of preliminary experimental studies, while reliability of the results obtained dramatically decreases even with a slight deviation of parameters outside the range studied.

Optimization of the technology is reduced to making special precautions to produce the preset configuration of the plasma flow and to proper selection of the 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 extrema of rates of variations in temperature of certain micro-volumes within certain time intervals.

Further increase in level of service properties of a part being hardened can be achieved through improvement of the hardening technology, which is eventually reduced to ensuring the optimal thermal

cycle (heating-cooling), proceeding from regularities in structural, phase and polymorphic transformations of the material hardened.
Stage 2 of the work involved development of the software for modelling the processes of structural, physical and chemical transformations occurring in the material studied, under substantially non-equilibrium conditions of rapid heating and cooling, proceeding from the fundamental up-to-date concepts of the processes being investigated. In principle, occurrence of these processes and variations in thermal conditions of the material treated are a single process. Thus, they should be computed simultaneously, because structural, phase and chemical
transformations are related in this or that way to absorption or release of latent heat. However, based on the fact that the available reliable literature data on thermal-physical properties of the material treated implicitly make allowance for the above processes (e.g. the data on specific heat include values of the effective apparent heat capacity, and the same applies to thermal conductivity) as well as that under the considered conditions of rapid heating and cooling the diffusion processes substantially lag behind the thermal ones, the above separation of the procedures of computation of thermograms and transformations in the material treated seems justifiable.
Difficulties of stage 2 are associated firstly with the absence of a common opinion concerning the process of formation of austenite during heating and its decomposition during cooling. Secondly, in the majority of the available literature sources describing investigations into the hardening processes for certain classes of materials, the data given are in the best case the result of mathematical processing (plots, tables) of experimental studies. And as a rule it is very difficult to get from them the information concerning mechanisms of the processes occurring and quantitative estimates of the processes taking place in an individual micro-volume, which are important for description.
For this paper the authors selected as a reference point a relatively small number of works, where all variations taking place in micro-volumes are described on the basis of fundamental concepts of the material and energy conversion processes.
The problem of modelling of the heat treatment process consists in computation of the quantity of austenite formed during the period of heating (in compliance with the thermogram plotted for a given micro-volume) and, accordingly, the percentage of that quantity of austenite which remains non-decomposed by the moment of achieving the martensitic transformation temperature at a stage of cooling.
Mathematical description of these transformation processes is based on the diffusion equation of the following form:

$$\partial C/\partial \tau = \partial[D(t)\cdot\partial C/\partial x]/\partial x,$$

where C is the carbon concentration, D(t) is the carbon diffusion coefficient depending upon the temperature t, x is the space coordinate, τ is the time recorded for each of the micro-volume structures allowing for their boundary conditions.
The latter depend upon the type of steel considered, whether it is hypueutectoid (containing ferrite and pearlite), eutectoid (containing only pearlite) or hypereutectoid (containing pearlite and cementite). In this case the conditions for free ferrite and ferrite which is part of pearlite are different. This is equally true for cementite. In addition, the type of the boundary conditions greatly depends upon the a priori simplified assumptions of the morphological peculiarities of individual structural elements of the micro-volume.
As an example, consider the case of hardening of eutectoid steel following the preset thermogram:

$$t=t(\tau), \qquad 0\le\tau\le T$$

where T is the total hardening time. In this case τ_1 is the moment of achieving the martensitic transformation temperature at the stage of heating, τ_2 is the moment of achieving a temperature of 727 °C at the stage of heating, τ_3 is the moment of achieving a temperature of 727 °C at the stage of cooling and τ_4 is the moment of achieving the martensitic transformation temperature at the stage of cooling:

$$T\ge\tau_1 + \tau_2 + \tau_3 +\tau_4$$

For the process of formation of austenite as a result of decomposition of cementite of the pearlite grain ($\alpha-\gamma$ transition), the following boundary and initial conditions ($\tau_2 < \tau \le\tau_3$) are valid:

at the cementite-austenite boundary

$$C(\tau,\xi_1) = C_{max}(t),\ D(t)\cdot\partial C/\partial x|x = \xi_1 = (0{,}0667 - C_{max}(t))\cdot d\xi_1/d\tau,\ \ 0\le x\le\xi_1$$

at the austenite-ferrite boundary

$$C(\tau,\xi_2)=C_{min}(t),\ D(t)\cdot\partial C/\partial x|x=\xi_2 = (0{,}0002-C_{min}(t))\cdot d\xi_2/d\tau,\ \ \xi_1\le x \le\xi_2 \le\xi_{2max}$$

$$\xi_1(\tau_2) = 0.5\cdot\delta Ce(\tau 2);\ \ \xi_2(\tau_2) = 0.5\cdot\delta Ce(\tau_2) + \delta A(\tau_2);$$

$$\xi_{2max} = 0.5\cdot(\delta F+\delta Ce+ \delta A)$$

Here:
$C_{min}(t)$ is the equilibrium carbon concentration in austenite at the boundary with ferrite (GS curve in the constitution diagram);
$C_{max}(t)$ is the equilibrium carbon concentration in austenite at the boundary with cementite (SE curve in the constitution diagram);
ξ_1 is the austenite-cementite boundary coordinate;
ξ_2 is the austenite-cementite boundary coordinate;
D(t) is the coefficient of diffusion of carbon into austenite;
δF, δCe, δA, $\delta F(\tau)$, $\delta Ce(\tau)$, $\delta A(\tau)$ are the thicknesses of the ferrite, cementite and austenite layers within the pearlite zone at the initial moment (τ=0) and arbitrary moment τ, respectively;
δA is determined from the value of the initial martensite content of steel.
For the stage of decomposition of austenite within the $\tau_1< \tau \le\tau_2$ and $\tau_3< \tau \le\tau_4$
ranges, it holds that:
at the cementite-austenite boundary:

$$C(\tau,\xi_1) = C^*_{max}(t),\ D(t)\cdot\partial C/\partial x|x = \xi_1 = (0{,}0667-C^*_{max}(t)) - d\xi_1/d\tau,\ \ 0\le x \le\xi_1$$

at the austenite-ferrite boundary:

$$C(\tau,\xi_2) = C^*_{min}(t),\ D(t)\cdot\partial C/\partial x|x = \xi_2 = (0{,}0002-C^*_{min}(t)) - d\xi_2/d\tau,$$

$$\xi_1\le x \le \xi_2\le \xi_{2max},\ \ \xi_1(\tau_1) = 0.5\cdot\delta Ce;\ \ \xi_2(\tau_1) = 0.5\cdot\delta Ce + \delta A;$$

where $C^*_{max}(t)$ and $C^*_{min}(t)$ are the continuations of the SE and GS curves into the range of temperatures below 727 °C, respectively.
Problems of stage 3 concerning development of the software, associated with construction of correlation models of the type of "material structure - physical-mechanical properties" are not considered within the frames of this paper.

3 Process equipment

Milestones in improvement of equipment are associated primarily with development and realization of new approaches, and in recent years with using measurement and control digital devices. Based on the above ideology, has developed and started up manufacture of a number of new high-tech plasma machines to implement new technologies.
To realize this idea, the Company developed plasmatrons designed for different power levels, as well as hardware for high-speed surface hardening of various parts.
The set of equipment for plasma hardening includes:
1.High-speed surface hardening machine UVPZ-2M (Fig.1),
2. A semi-automatic line for hardening of wheelsets with wheeling out (Fig. 2)
The UVPZ-2M machine is equipped with an independent optimization unit to provide:
- in-process programming of conditions and parameters, indication of the current condition of the controlled process parameters, recording and storing of parameters of the process of plasma surface

hardening of wheelsets in permanent memory and output of the information accumulated to a personal computer;
- processing of analogue signals from the "Smotrich" pyrometer, the plasmatron power supply and pressure sensors, as well as input discrete signals from the final control mechanisms and formation of output commands for programmed control.

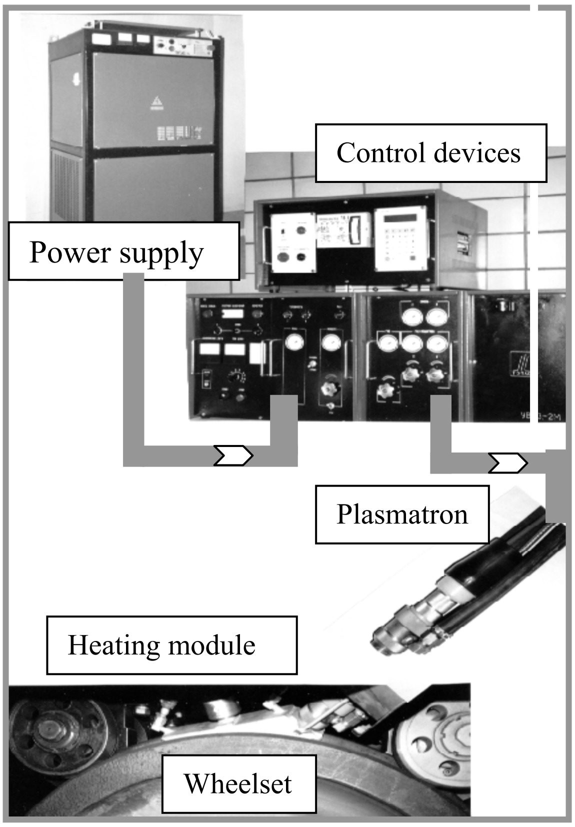

Fig. 1. High-speed surface hardening machine UVPZ-2M

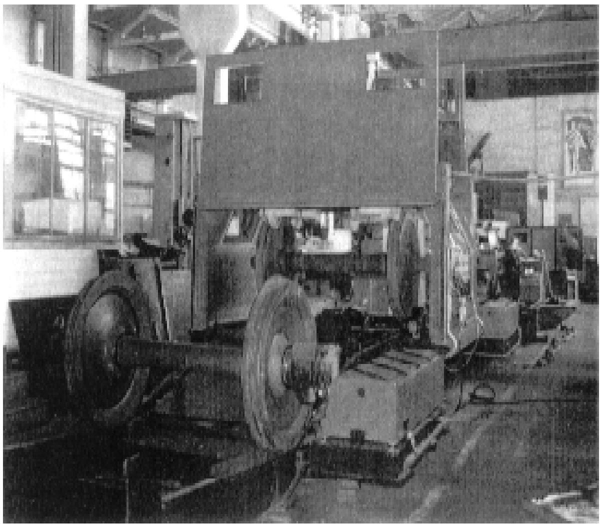

Fig. 2. A semi-automatic line forhardening of wheelsets with wheeling out

4. Results of wheelsets 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 locomotive wheelsets. Intensity of wear of the wheelset ridges after plasma hardening is much lower than that of the traditionally treated ones (2.5-3 times). The developed technology for hardening of the wheelsets has two peculiar features: 1.local (within the zone of the highest wear) surface hardening of the wheel ridge 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.

Locomotives with the wheels plasma hardened technology were first 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 by the end of April 1996 the expected two-fold decrease in rate of 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. (Fig. 3). 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 5 years operation of locomotives and cars with the plasma hardened wheelset ridges 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.

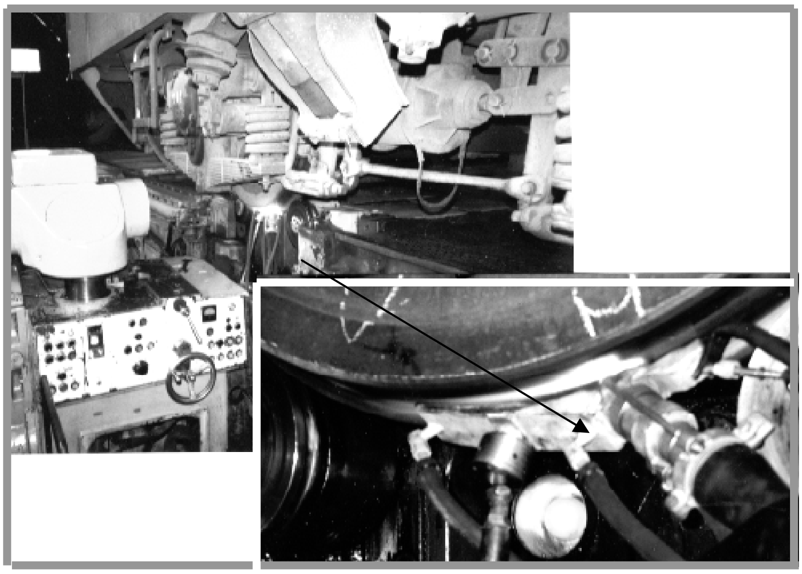

Fig.3. Plasma hardening of wheelsets without wheeling out from under a locomotive

5.Tempering of flats

A new technology for high-speed plasma tempering of cold-worked (hardened) roll surfaces of wheelsets has been developed on the basis of the UVPZ-2M machine. This technology has been successfully applied at a number of depots (Fig.4) 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.

6. Plasma Spraying of Resistant Coatings on Wheel Flanges

Constant shape of a wheel flange is ensured by deposition of wear-resistant coatings. This solves a contradictory problem, i.e. maintaining a sufficiently high coefficient of friction between the roll surface and rail to improve transfer of longitudinal forces and decreasing friction in the zone of pressing of the lateral face of the flange to the rail.

Wear-resistant coating of a self-fluxing material with an addition of carbides or carbonitrides (Fig.5) is deposited on the wheel flange in one pass with a simultaneous surface melting. Thickness of the coating is 1-2 mm, width of the coated strip is 25-30 mm. This is done using the rotators, or rotators for wire deposition of the flanges, as the spray surface should be in a horizontal position. Wear-resistant coatings with simultaneous surface melting can be deposited using the UVPZ-2M plasma equipment for surface hardening, subjected to upgrading.

Materials which provide the following properties were selected for deposition of the coatings:

- high toughness and deformability of the deposited layer;
- special properties of the coating material the friction coefficient of which corresponds to a minimum probability of derailment;

- low wear of the rail-wheel system;
- high strength of adhesion of the coating to the substrate material;
- homogeneous structure of the coating;
- long service life of the coating;
- possibility of repeated deposition without preliminary machining.

Such a coating will provide a 5-10 times extension of life of the flange and a decrease of 50-100 % in the coefficient of friction of the working surface of the flange with the rail.

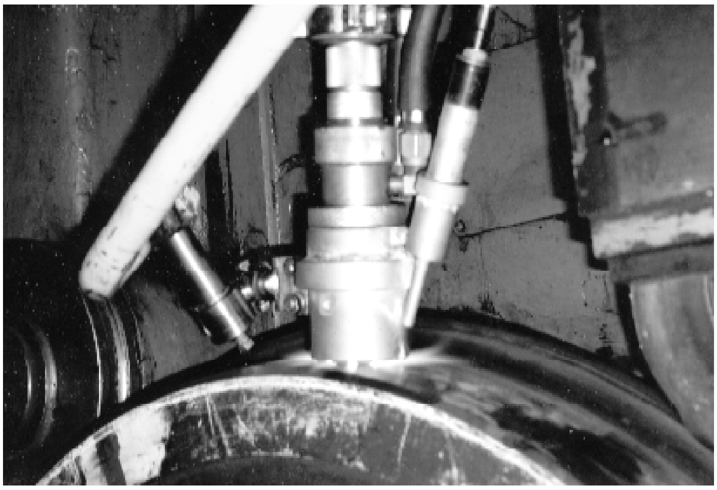

Fig.5. Tempering of flats

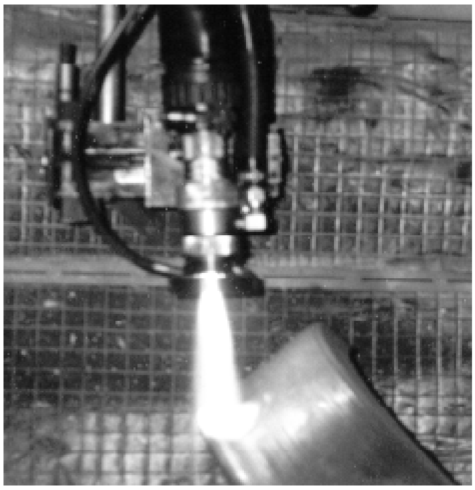

Fig.6. Plasma Spraying of Resistant Coatings on Wheel Flanges