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CONDENSED-STATE PHYSICS

STRESS STATE IN DEPOSITED STEEL CAST ROLLS WITH HIGH SURFACE HARDNESS AFTER ARGON PLASMA-JET HARD-FACING

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*The method based on the stress redistribution from principal to new ones near the machined groove combined with X-ray diffraction analysis is used to investigate the stress state of the cast rolls deposited with the P2 M9 steel having a high surface hardness obtained by the plasma-jet hard-facing in argon. It is shown that the stress state in the deposited cast rolls is more favorable for their operation than that in rolls fabricated by the conventional technique. The stress distribution over the deposited cast roll is characterized by a gradual transition from compressive residual stress of 600 MPa in the deposited layer to tensile stress of 200 MPa in the base metal. The increase in the wear resistance of the deposited cast rolls can be explained by the α-*Fe *solid solution and finely dispersed iron, tungsten, chromium, molybdenum, and aluminum carbonitrides presenting in the steel structure and the favorable stress state in the surface layer formed by the thermal cycle of the argon plasma-jet hard-facing accompanied by the low-temperature heating followed by high-temperature tempering.*

Keywords: argon plasma-jet hard-facing, high-temperature tempering, stress state, stresses relaxation in a groove, X-ray diffraction analysis, compressive stress, finely dispersed carbonitrides.

INTRODUCTION

Residual stresses significantly affect the wear resistance of cold rolling rolls. At a high level and unfavorable distribution, residual stresses together with the contact and heat stresses, cause early fracture of the roll effective layer. Knowledge of the residual stress distribution and control for its formation allow reducing the negative stress effect on the roll lifetime. This is especially important for changes in the roll production process including quenching, effective layer deposition, and steel grade for the roll production. The reliability and lifetime of cold rolling mill work rolls can be improved by the formation of a favorable stress state in them [1, 2]. Solid forged steel rolls are usually made of 9Kh and 9Kh2V steel grades. The roll production is a complicated process, which makes them rather expensive. The required high and uniform hardness of the effective layer, its depth and favorable stress state in the rolls can be achieved by various heat treatment techniques. Plasma-jet hard-facing with heat resisting steels of high hardness solves these problems, including the formation of the favorable stress state in the roll.

Siberian State Industrial University (Novokuznetsk, Russia) has developed the production technique of cold rolling mill work rolls by using plasma-jet hard-facing of the effective layer [3]. This production technique includes the

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preliminary machining of the roll workpiece for the effective layer deposition, high-temperature tempering, finishing, quality control. Polishing by abrasive machining may lead to the structural and phase transformations in the surface layers of materials [4, 5].

The base metal for the roll was 30HGSA steel grade. The effective layer was obtained by argon plasma-jet hard-facing using R2M9, R3M2, R5M5, R18 heat resisting steels, which more fully met the requirements for the surface layers operating in abrasive wear conditions [2]. The Rockwell C scale hardness (HRC) value of the deposited metal ranged between 55 and 57. The successive high-temperature tempering was used for a complete transformation of the austenite residue and an increase in the tempering hardness of the deposited effective layer. After such treatment, the HRC hardness of the surface layer was 62–64. The industrial tests of the deposited cast rolls demonstrated the HRC value 1.5 or 2 times higher than that of the rolls made of 9Kh steel grade.

Calculation, experimental non-destructive and destructive testing methods were used to determine the residual stresses in cold rolling rolls [1, 2]. Application of the calculation methods was limited by the lack in the experimental data concerning the specific deposition process. Most of the data on residual stresses in rolls was obtained using methods relating to the product fracture. These deposition methods should primarily include the Davidenkov–Zaks method. It was however difficult to employ because of the complicated machining of the deposited layer with 62–64 HRC.

Mikhailov and Suleimanov [5] proposed a method to determine the residual stresses in work rolls with the high surface hardness. The method was based on the stress redistribution from principal to new ones near the stress concentrator (a shallow straight groove). The main limitations of that method were associated with abrasive machining, which left behind a wide heat-affected zone significantly disturbing the measurement accuracy.

There is little information in the literature about the stress state of deposited cast rolls obtained by the up-to-date measurement techniques. It is not yet clear why the deposited parts have enhanced the wear resistance. The aim of this work is to determine the stress state of the deposited cast rolls with the high surface hardness obtained by argon plasma-jet hard-facing, up-to-date measurement techniques, and to clarify why these rolls have enhanced wear resistance.

MATERIALS AND METHODS

The stress state was investigated in the deposited heat resisting, high-hardness steel of the grade P2 M9 (USA analog M7), additionally alloyed by aluminum and nitrogen. Its chemical composition was 0.86 wt.% C, 4.8 wt.% Cr, 2.50 wt.% W, 9.40 wt.% Mo, 0.50 wt.% V, 0.85 wt.% Al, 0.08% N, and the iron residue. The grade 30HGSA low-alloy steel possessing high mechanical properties was used as a base metal; its chemical composition was 0.3 wt.% C, 0.9 wt.% Cr, 0.8 wt.% Mn, 0.9 wt.% Si, and the iron residue.

Plasma-jet hard-facing machine was used for a body of rotation in the thermal cycle, which included a preliminary and additional low-temperature heating, interim temperature drop, and exposure to this temperature [2]. The rolls were deposited with a plasma jet and then delivered to the molten pool of non-conducting flux-cored wire PP-R2M9Yu. Argon and nitrogen were used as forming and protective gases, respectively. The workpiece oversized by 5–10 mm for hard-facing was placed at the center of the plasma-jet hard-facing machine and pre-heated up to 230°C. The roll necks were then cooled in water at a speed of 2 L/min. A deposition of five or six layers was performed at 150−160 A current, 50−55 V voltage, 18 m/h velocity, 60 m/h wire feed speed, 10–12 mm zenith displacement, 20 mm arc length, 20−22 L/min nitrogen gas rate, 6−8 L/min argon gas rate, and 3.7 mm wire diameter. After hard-facing, the workpiece was cooled in air. Neither intrinsic or surface defects such as pores, cracks, and slag inclusions, were found in the deposit after the ultrasonic and magnetic flaw detections. The obtained steel surface demonstrated the satisfactory quality.

After plasma-jet hard-facing, the rolls underwent the high-temperature tempering, which satisfied the recommendations for P2 M9 steels, i.e., 580°C, 1 h exposure, and 4 exposures [2].

Residual stresses were investigated at the roll body center at a distance from the ends of not less than its diameter. Electromachining on a working machine 4840 was used to fabricate a 20 mm thick disk from the central part of the roll in the working fluid.

Residual stresses in deposited cast rolls with the high surface hardness were determined by the improved machined groove method [6] consisting of the following procedures: 1) disk electromachining from the roll body center, 2) disk surface polishing, 3) strain gauge installation and test circuit assembly, 4) electrical discharge machining (EDM) of the straight groove using a copper plate electrode 0.6–0.8 mm thick at different depths, 5) measurement of additional tangential stresses at h_i and h_j groove depths using a strain gauge, 6) tangential stresses analysis for the disk using the groove equation, 7) residual stress analysis in the roll using the groove equation [5].

Tangential stresses in the disk are calculated by the machined groove method with regard to the shape and side of the groove [5]:

$$\sigma_\theta^0 = \frac{E\delta_e \Delta D_{0,i-j}}{\Delta V_{0,i-j}}, \tag{1}$$

where $D_{0,i-j} = D_{0i} - D_{0j}$, D_{0i}, D_{0j} are additional tangential stresses on h_i and h_j groove depths in rheochord graduations of the strain gauge, V_i and V_j are the sensitivity coefficients determined for the strain gauge at its certain installation relative to the groove with h_i and h_j depths using the dependence proposed in [5], $\delta = 10^{-5}$ is the strain gauge sensitivity, E is the elastic modulus of the metal deposit.

An automated strain gauge AID–4 and 2PKB–10–200 wire resistance strain gauge with a 10 mm base were used to measure deformation. The residual stresses were investigated at the center of the roll body distant from the roll ends in order to increase the number of measurement points in the deposited metal. With such an arrangement of strain gauges on a disk of a 100 mm diameter, the measurement points could amount to 40. The elastic modulus of the deposited and base (30HGSA) metals was accepted to be $22.1 \cdot 10^{-4}$ and $20.2 \cdot 10^{-4}$ MPa, respectively. The obtained data were processed in a specially developed software.

The X-ray diffraction (XRD) analysis was carried out by DRON-3 diffractometer [7]. Using kerosene as a working fluid in EDM, the deposited metal specimens were cut into several parts. The test specimen surface was sanded using fine sandpaper and diamond paste, and the deformed layer was then subjected to electroetching. An 80 mL H_3PO_4 + 6 g Cr_2O_3 + 14 mL H_2O electrolyte was used for electromachining of these specimens. Electromachining of all types of layers was conducted at 10–70 V electrode voltage.

The XRD analysis was conducted for the surface, central part of the hard-facing, fusion area between the deposited and base metals from the hard-facing side. X-ray diffraction patterns of the deposited layers were recorded at continuous scanning in the 2θ range using Bragg-Brentano geometry and copper radiation (K_α) (λ = 1.54051 Å). The crystal phase identification was performed with the use of the JCPDS/ICDD PDF-2 software and database [8–11]. As a result, the crystal lattice parameters, microdistortion, and coherent scattering regions (CSR) were identified.

RESULTS AND DISCUSSION

In Fig. 1, the tangential stress distribution suggested for the disk is based on the data processing of nine disks cut from three deposited cold rolling mill work rolls with a diameter of 100 mm. One can see the high compressive stresses in the deposited layer, which reach 550–600 MPa near the surface. At a distance comparable with the thickness of the deposited layer of ~10 mm, these compressive stresses transit to tensile. The maximum tensile stress in the base metal is 200 MPa.

The tangential stress distribution in the disk is used to calculate the residual stress components in the whole roll [9]:

$$\sigma_r^0 = \sigma_r^d - \sigma_r^{add}, \tag{2}$$

$$\sigma_\theta^0 = \sigma_\theta^d - \sigma_\theta^{add}, \tag{3}$$

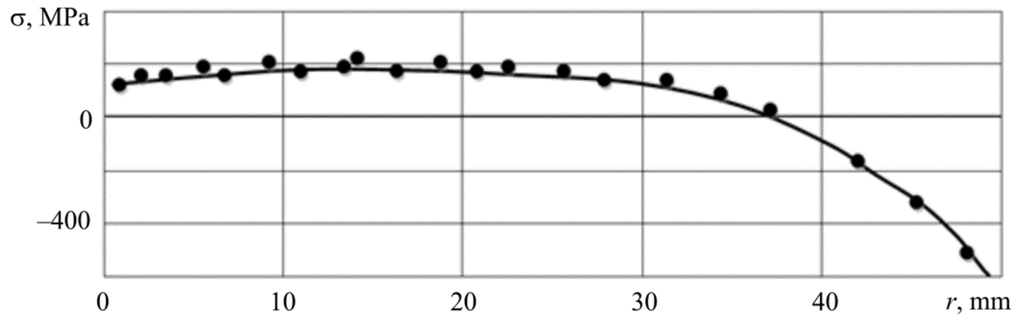

Fig. 1. Tangential stress distribution in disk. *r* is the distance between the roll center and strain gauge.

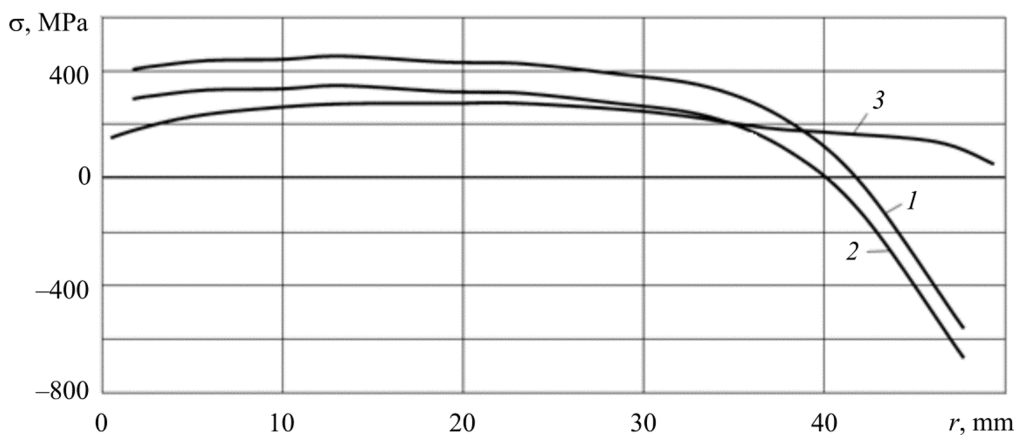

Fig. 2. Three-dimensional stress distribution in deposited work roll: *1* – axial stress, *2* – tangential stress, *3* – radial stress.

$$\sigma_z^0 = \sigma_z^d - \sigma_z^{add}, \quad (4)$$

where σ_r, σ_θ and σ_z is the radial, tangential and axial stresses, respectively; indices *d*, 0 and *add* denote stresses in the disk, in the roll, and additional stress, respectively. Unknowns in this equation are determined by the equations from [5].

Figure 2 presents the residual stress distributions in a set of deposited work rolls. The change in the axial and tangential stresses matches the tangential stress distribution in the disk with the maximum compressive stress of about 700 MPa.

The three-dimensional stress distribution in the deposited work roll is described by a continuous transition of compressive stresses in the deposited layer to tensile stresses in the base metal. The maximum tensile stresses are observed ~30 mm deep in the base metal and amount to $\sigma_z = 480$ MPa, $\sigma_\theta = 400$ MPa, $\sigma_r = 240$ MPa. This residual stress distribution in deposited work rolls can be explained by their processing technique, namely plasma-jet hard-facing and high-temperature tempering in the first place. The processing technique for deposited work rolls enables compressive stresses in the surface layer. The continuous compressive-to-tensile stress transition prevents tensile stresses from a drastic peak. This technique increases the lifetime of the deposited cast rolls [2].

Figure 3 shows the residual tangential stress distribution in the deposited cast rolls (curve *1*) and rolls fabricated by the conventional tempering technique using 9Kh steel (curve *2*) [2]. According to Fig. 3, the stress state in the deposited cast rolls is more favorable for their operation than that in rolls fabricated by the conventional technique. The tempered rolls manifest a drastic peak of the compressive-to-tensile stress transition that negatively affects the roll operation [1].

TABLE 1. Stress State Parameters of Nitrogen-Alloyed Heat Resisting Steel after Plasma-Jet Hard-Facing and High-Temperature Tempering

Processing techniques	Stress state	*a*, Å, α-Fe	*D*, nm, α-Fe	$\Delta d/d \cdot 10^{-3}$, α-Fe	$\tau = \Delta d/d \cdot E$, MPa
Plasma-jet hard-facing	Surface	2.885	25	3.3	730
	Central part of the hard-facing	2.869	50	4.8	1060
	Fusion area from the hard-facing side	2.868	50	4.7	1040
Steel hardening with tempering	Surface	2.887	100	1.7	380
	Central part of hard-facing	2.880	100	3.0	660
	Fusion area from the hard-facing side	2.887	100	3.5	770

Notation: $\Delta d/d$ –crystal lattice microdistortion, *d* – interplanar spacing, Δd – difference in the interplanar spacing, *D* – CSR size.

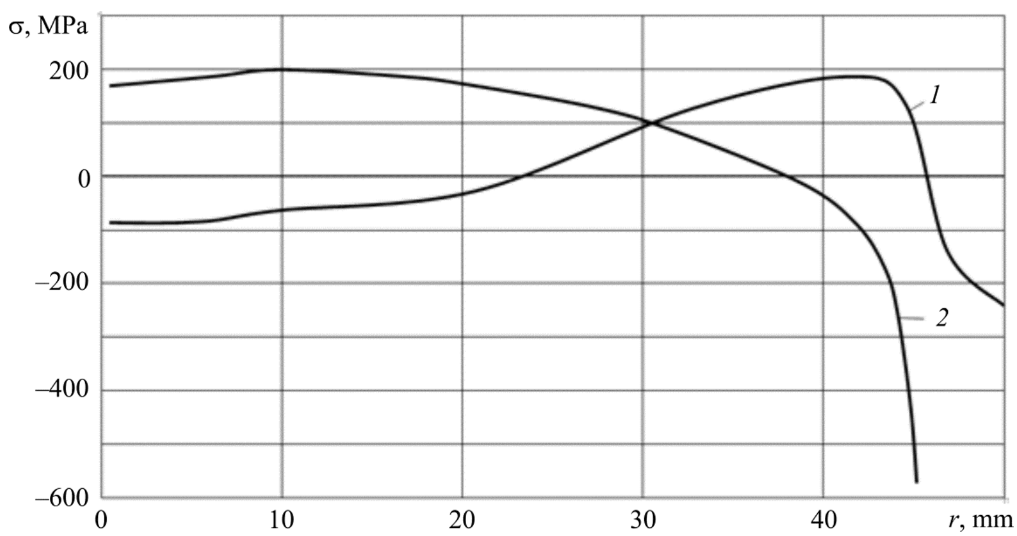

Fig. 3. Residual tangential stress distribution in deposited work rolls: *1* – tempered roll fabricated by the conventional technique, *2* – deposited cast roll.

Table 1 summarizes the stress state parameters of the nitrogen-alloyed heat resisting steel after plasma-jet hard-facing and high-temperature tempering identified by X-ray crystallography.

The width of the XRD patterns allows detecting two types of the crystal lattice distortion [8–11]. First, internal stress and, second, the CSR size. The latter is an inverse value relative to the defect spacing. The experimental data are presented in Table 1. The CSR and $\Delta d/d$ values vary from 25 to 100 nm and from 1.7 to 4.8, respectively. These values correspond to the internal elastic stress $\tau = \Delta d/d \cdot E$ (*E* is Young's modulus), which ranges between 540 and 940 MPa. In other words, the level of internal stresses is rather high (940 MPa) in the deposited metal soon afterwards the hard-facing. After the high-temperature tempering at 540 MPa, these stresses are about 2 times lower due to the stress relaxation in steel specimens. The defect spacing ranges between 25 and 50 nm in the initial state and is ~100 nm in the tempered state. The high-temperature tempering leads to a considerable defect reduction, which, in turn, reduces internal elastic stresses in the steel.

In our research [7], we found that the structure and phase composition of the nitrogen-alloyed heat resisting steel after plasma-jet hard-facing, consisted of the α-Fe solid solution and finely dispersed iron, tungsten, chromium, molybdenum, and aluminum carbonitrides, the main alloying elements being distributed uniformly. The high-

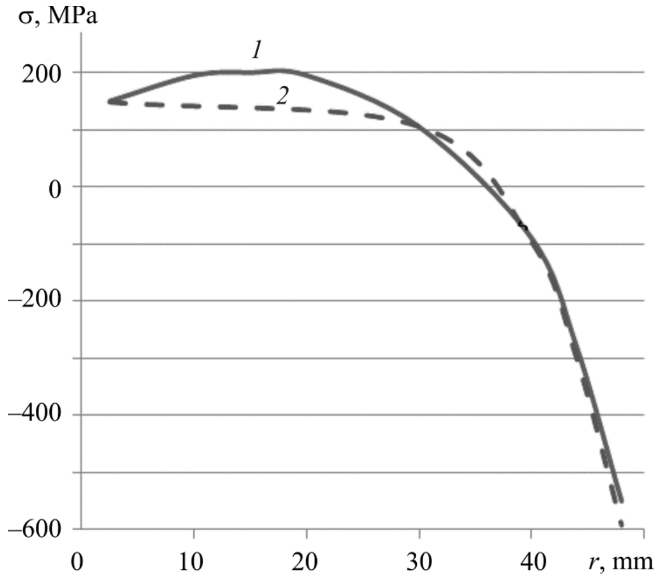

Fig. 4. Residual tangential stress distribution in deposited work roll: *1* – experimental curve, *2* – theoretical curve.

temperature tempering of the deposited steel modified the phase composition, crystal lattice parameter, CSR size, and internal elastic stresses.

According to the comparative analysis of the stress state parameters obtained by the improved technique of the stress redistribution near the machined groove combined with the XRD analysis, the tangential stresses in the disk with the highest compressive stress are ~700 MPa and 660–770 MPa, respectively. These comparable values allow us to recommend the proposed technique for the identification of the stress state in deposited parts with the high surface hardness.

The detection of the residual compressive stress by using the machined groove method combined with the XRD analysis, is rather laborious. Therefore, we propose the mathematical model for the identification of the stress redistribution in the deposited cast rolls. For this, the software program "Statics and Stability of Medium Thickness Roller Shells" is developed at the Mathematics and Mathematical Simulation Department of Kemerovo State University (Kemerovo, Russia), which is based on the finite element method and the theory of shells developed by Timoshenko [12]. The deposited cold rolling mill work roll with a diameter of 100 mm and length of 315 mm is considered as a roller shell of a medium thickness. The meridian line is set in the program for the shell as well as its structure, mechanical properties, thickness of the deposited layer, load and temperature distribution for each layer deposited. The base metal is 30HGSA steel, the deposited layer is P2 M9 steel. The shell is split into finite elements using the third-order Hermite interpolation [12].

The model adequacy to the deposited cast rolls is checked by a comparison of the residual tangential stress values obtained in the experiments and numerical calculations (see Fig. 4). The difference between these values is insignificant.

SEM images of the surface structure of the deposited cast rolls after the high-temperature tempering are presented Fig. 5 for the central part of the hard-facing and the fusion area between the deposited and base metals. According to this figure, the hard-facing defects such as pores, cracks, slag inclusions and defects in the structure are absent in the deposited layer, which has a positive effect on the roll resistance.

Pilot run testing of the deposited cast rolls showed that their wear resistance increased by 1.5–2.0 times. This was because the presence of the α-Fe solid solution and finely dispersed iron, tungsten, chromium, molybdenum, and aluminum carbonitrides in the structure as well as the creation of the favorable stress state and compressive stresses in

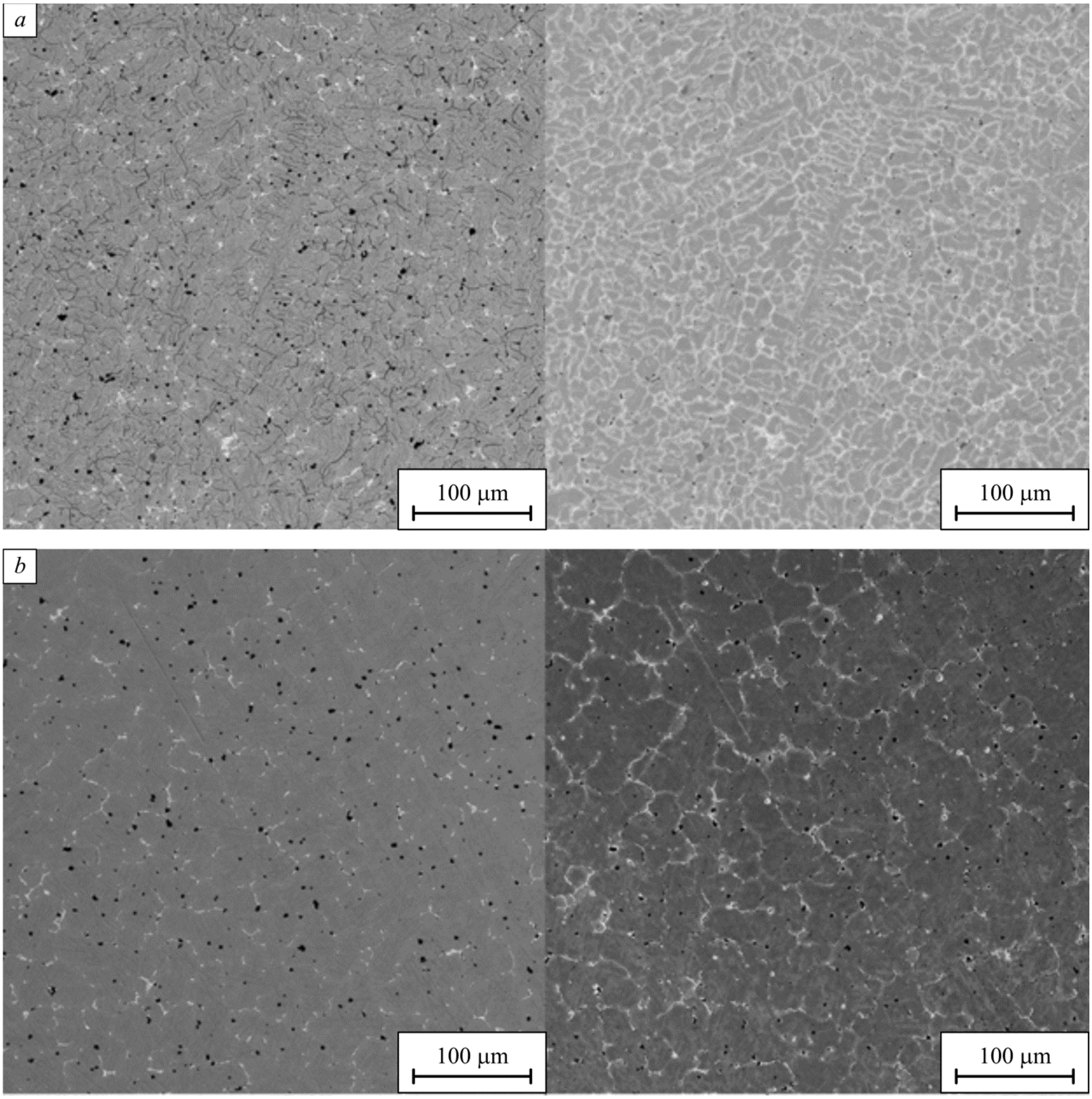

Fig. 5. SEM images of deposited layer after high-temperature tempering: *a* – central part of hard-facing, *b* – area between deposited and base metals.

the surface layer due to the thermal cycle of the argon plasma-jet hard-facing accompanied by the low-temperature heating.

CONCLUSIONS

Based on the results it can be concluded that the residual stress distribution in the deposited cold rolling mill work rolls with the HRC value of 55 to 64 in the effective layer could be identified by the proposed machined groove method, which utilized EDM with a copper plate electrode and disk electromachining from the roll body center. It was shown that the stress state in the deposited cast rolls was more favorable for their operation than in rolls fabricated by the conventional tempering technique using 9Kh steel. The stress distribution over the deposited cast roll was characterized by a gradual transition from compressive residual stress in the deposited layer to tensile stress in the base metal. Such a residual stress distribution in deposited work rolls could be explained by their processing technique, namely plasma-jet hard-facing and high-temperature tempering in the first place and the presence of the α-Fe solid solution and finely dispersed iron, tungsten, chromium, molybdenum, and aluminum carbonitrides in the deposited layer.

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