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# STRENGTHENING OF METALLURGICAL EQUIPMENT PARTS BY PLASMA SURFACING IN NITROGEN ATMOSPHERE

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The present work is aimed at improving the method of multilayer plasma surfacing under a shielding-alloying nitrogen atmosphere. The article presents comparative studies of residual stresses formed by surfacing with 3Kh2V8, 4Kh4V10Yu, and R18Yu steel wire. The R18Yu-based wire product is shown to provide the lowest residual stresses. In addition, the improved method of multilayer plasma surfacing with heat-resistant steels under a nitrogen atmosphere is presented as preventing crack formation and increasing the hardness of the surface metal without subsequent heat treatment. Based on the results of the study, multilayer surfacing together with ferrochromium and titanium additives to the composition of the surfacing wire can be used to obtain a metal not prone to cracking in a close to hardened metal state.

**Keywords:** surfacing method, controlled thermal cycle, flux-cored wires, nitrogen, hardness, heat-resistant steels.

Heat-resistant high-hardness steels, such as R18, R6M5, R2M9, and others, are widely used as surfacing materials for strengthening machine parts of mining and metallurgical equipment operating under abrasive wear conditions. Despite high service characteristics, these steels are characterized by poor weldability [1, 2]. The traditional surfacing technology used for such steels involves the mandatory use of high-temperature pre- and concurrent heating for the prevention of the cold crack formation. Here, the concurrent heating temperature $T_{\text{conc}}$ typically comprises 400–700°C. In addition, the traditional technology involves slow cooling of the product after surfacing to eliminate cracking of the surface layer. The concurrent heating of the product and its smooth cooling leads to the formation of an equilibrium structure characterized by low hardness and wear resistance. This, in turn, necessitates subsequent complex heat treatment in the form of annealing, hardening, and tempering to ensure maximum hardness of the product surface [3, 4].

In this connection, a method for surfacing with high-hardness heat-resistant steels has been developed at the Siberian State Industrial University. In order to prevent cold crack formation, this method uses the effect of increased plasticity (“superplasticity”) and controlled low-temperature concurrent heating. The developed method promotes for obtaining an uncracked surface layer in a state close to hardened. Such an approach is optimal for surfacing rotational parts (rollers, mill rolls, shafts, etc.). The developed method is based on the process of

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plasma surfacing at reverse polarity under a shielding-alloying nitrogen atmosphere with a non-conducting filler flux-cored wire. The selection of plasma surfacing as a method for applying wear-resistant coatings can be explained by a number of advantages over other surfacing methods. These include high productivity, the wide range of possibilities for alloying the surface metal, as well as the option of using various surface metals. In terms of a heat source, a feature of the constricted (plasma) arc consists of its thermal and gas-dynamic characteristics, which can be easily adjusted across a wide range. The use of the reverse polarity constricted arc reduces labor-intensive procedures that complicate technological surfacing processes due to the need for surface pre-cleaning [5, 6]. In this case, cleaning of the surface from contamination is performed directly within the process of surfacing due to the effect of cathode sputtering. At the same time, the necessary conditions for the adhesion of the surfaced product to the surface metal and defect-free formation of the surface layer are provided. Moreover, during the reverse polarity surfacing, a smaller dilution of the surface metal with the base metal is achieved [7]. In comparison to argon, the use of nitrogen in terms of a protective gas ensures not only a reduction in the cost of surfacing, but also the effective alloying of the surface metal with nitrogen from the gas phase directly during the surfacing process, which significantly increases the hardness and wear resistance of the metal [8].

The resistance of the metal against the cold crack formation can be changed within certain limits by adjusting the increase in the welding tensile stresses during its cooling. The essence of such regulation consists in the selection of the surface metal chemical composition by changing the composition of the flux-cored wire charge. The chemical composition of the flux-cored wire charge ultimately determines the linear expansion coefficient together with the nature and volumetric effect of structural transformations [9, 10]. These factors have a significant effect on the development of tensile stresses in the process of surfacing. During the study of the increased plasticity effect for the R18 and 3Kh2V8 alloys, the alloying degree was noted to have a definite effect on the relaxation of tensile stresses. The magnitude of residual stresses can be controlled by shifting the curve of the tensile stress formation to lower temperatures due to appropriate alloying of the surface metal [11]. Tensile stresses accumulated in the austenite region during the metal cooling relax in the martensitic transformation range and do not develop further upon cooling to room temperature [12, 13].

*The present study is aimed* at improving the method of multilayer plasma surfacing in a shielding-alloying nitrogen environment. Changes made to the surfacing process are directed at reducing both the magnitude of residual stresses in the formed surface layer and the probability of cold cracking.

## Materials and Methods

At the first stage of the study, three types of samples with a surface layer were obtained. Wires made of 3Kh2V8, 4Kh4V10Yu, and R18Yu steels were used as the material for surfacing. The primary material to which the surfacing was applied consisted of 30KhGSA steel having high mechanical properties and containing (%): 0.3 C, 0.9–1.1Cr, 0.8-1.1 Mn, and 0.9–1.2 Si.

The workpiece was surfaced using a unit for plasma surfacing of rotational parts [14]. The rolls were surfaced using a plasma arc by introducing the PP-R18Yu non-conducting filler flux-cored wire into the weld pool. Argon and nitrogen were used as plasma-forming and protective gases, respectively. A workpiece with surfacing allowances of 5–10 mm per side was installed in the centers of the surfacing unit and preheated to a temperature of 230°C, followed by the roll neck cooling with a flow rate of cold water up to 2 Liter/min. After completion of the preparatory operations, a five- or six-layer surfacing process was carried out. Surfacing mode: $I_{\text{weld}}$ – 150–160 A; $U_{\text{A}}$ – 50–55 V; surfacing rate $v_{\text{surf}}$ – 18 m/h; flux-cored wire feeding rate $v_{\text{wire feed.}}$ – 60 m/h; offset from the zenith 10–12 mm; arc length $l_{\text{a}}$ – 20 mm; protective gas (nitrogen) consumption $Q_{\text{protect}}$ – 20–22 Liter/min; plasma gas (argon) consumption $Q_{\text{plasma}}$ – 6–8 Liter/min; wire diameter – 3.7 mm.

After surfacing was completed, the workpiece was cooled in air. Plasma surfacing was carried out according to the thermal cycle with low-temperature concurrent heating. No welding defects were found during visual inspection and ultrasonic testing of parts. The quality of the obtained surface was established as satisfactory.

Next, samples were cut from the upper layers of the surface metal using an electric spark cutting machine. Half of the samples from the batch were subjected to heat treatment in the modes, selected for surface samples according to the recommendations for R18 forged steels with similar composition (heating temperature – 580°C; holding time – 1 h; number of temperings – 4) [10, 14].

The study of the obtained samples was carried out in two states: directly in the state after surfacing and in the "surfacing + high-temperature tempering" state. For the research, the samples were cut by an electric spark machine into several parts in kerosene and mechanically smoothed using fine sandpaper and diamond paste. After that, the deformed layer was electrolytically etched and the surface was smoothed. The samples were electropolished using an electrolyte of the following composition: 80 mLiter $H_3PO_4$ + 6 g $Cr_2O_3$ + 14 mLiter $H_2O$. All types of substrates were electropolished at an electrode voltage of 10–70 V. Sample surfaces were etched in a 2% nitric acid solution.

The structural-phase state of the samples was studied by X-ray diffraction analysis (XRD) using a DRON-3 instrument. The X-ray diffraction patterns of the surface samples under study were recorded in continuous $2\theta$-scanning mode with Bragg-Brentano focusing using Cu anode (radiation wavelength $CuK_\alpha$ = 1.54051 Å). The identification of crystalline phases was carried out using the JCPDS PDF-2 database of the ICDD structural catalogue. In addition, the structural-phase state of the surface metal was studied by scanning electron microscopy (SEM) and electron probe microanalysis (EPM) using a Leo EVO 50XVP instrument (Carl Zeiss, Germany) on etched sections on the surface and in the central part of the sample.

The alteration of thermal tensile stresses in rigidly fixed samples of 3Kh2V8, 4Kh4V10Yu, and R18Yu surface steels was carried out using an IMASH-5S-69 thermal microscopy unit.

## Results and Discussion

In order to achieve the determined goals, the effect of the surfacing wire composition on the formation of tensile stresses in the surface layer was studied. Surfacing was performed using wire consisting of three different alloy steels: 3Kh2V8, 4Kh4V10Yu, and R18Yu. For obtained samples, thermal tensile stresses were measured during cooling of the surface samples from a temperature of 1200°C. Figure 1 shows the results of these measurements. As can be seen from the data in Fig. 1, for a surfacing wire made of R18Yu steel (curve 1), when the samples are cooled from a temperature of 1200°C, the effect of increased plasticity (superplasticity) is observed during phase transformation. This effect manifests itself as decreased tensile stresses in the temperature range of martensitic transformation. In this range, tensile stresses are reduced by 1.5–2 times compared with the magnitude of the stresses accumulated in the austenitic region. At further cooling, the stresses increase to 120–130 MPa due to some increase in the amount of martensite. According to the results of the study, the effect of increased plasticity is observed at the time of the martensitic transformation in heat-resistant high-hardness steels.

Residual stresses in the samples with a 3Kh2V8 steel wire surface layer comprise ≈ 200–210 MPa (see Fig. 1, curve 3) versus ≈ 145–155 MPa in the samples with a 4Kh4V10Yu steel wire surface layer (see Fig. 1, curve 2). This can be explained by a shift in the position of the formation curve for 4Kh4V10Yu steel tensile stresses to lower temperatures. This shift appears to be a consequence of the higher content of alloying elements (chromium, carbon, and aluminum) in the surface layer. The use of R18Yu steel in terms of the welding wire material contributes to an even greater increase in the concentration of carbon and tungsten in the surface layer and leads to a shift in the temperature range of stress relaxation to even lower temperatures. No significant

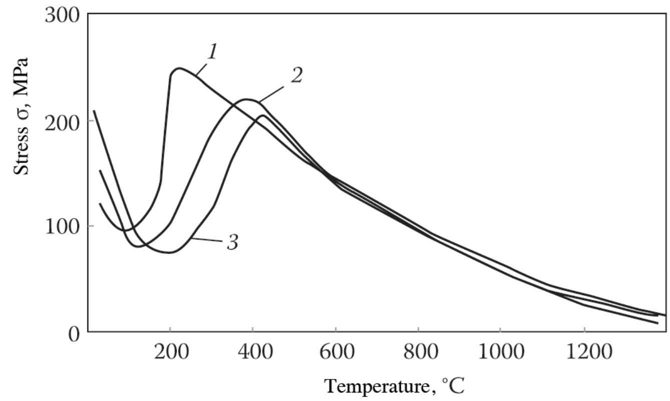



**Fig. 1.** Formation of residual stresses during cooling of samples in a surface layer made using various steel wires: *1* — R18Yu; *2* — 4Kh4V10Yu; *3* — 3Kh2V8 ($T_s$ = 1200°C).

development of tensile stresses after relaxation in the region of martensitic transformation is observed; moreover, the residual stresses in the R18 steel surface layer turn to be even lower than in the 4Kh4V10Yu layer. The formation of a surface layer with a high content of carbon, chromium, tungsten, and aluminum contributes to the preservation of finer austenite grains. The completeness of using martensite transformation in terms of a mechanism for relaxation of internal peak stresses depends on the degree of martensite dispersion. Apparently, this also explains the high degree of tensile stress relaxation in the R18 steel.

Thus, the R18Yu steel appears to be the optimal surfacing wire material in terms of the formation of minimal residual stresses. Accordingly, further studies of the formed microstructure in the surface layer, as well as the selection of the optimal composition of the surface wire, were carried out for this material. Steel 30KhGSA remained the base material for surfacing.

During constricted arc surfacing in nitrogen-containing gaseous media, intense boiling of the weld pool is observed, since the interaction of the liquid metal in the weld pool with the gas phase during the surfacing process leads to the saturation of the metal with nitrogen. When the metal is crystallized, the solubility of nitrogen in it decreases sharply, releasing excess nitrogen which contributes to the formation of porous structure caused by the transience of the surfacing process. In order to eliminate porosity, the core of the flux-cored wire based on R18Yu steel was admixed with aluminum binding excess nitrogen into compounds insoluble in the liquid metal (aluminum nitride). Such compounds partially float to the surface of the weld pool, as well as remaining in the surface layer and acting as an additional hardening phase [15, 16]. The probability of cold crack formation also decreases at reduced hydrogen content in the surface layer (hydrogen hypothesis of cold crack prevention). The hydrogen content in the surface layer was reduced by additives of silicon fluoride, sodium aluminofluoride or aluminum filter dust to the core of the flux-cored wire. The possibility of using nitrogen protective gas instead of argon results in additional strengthening of the surface layer due to alloying it with nitrogen from the gas phase directly during the surfacing process. As a result, the formed surface layer is not prone to cracking and is in a state close to hardened metal. Thus, no subsequent hardening is required to obtain high hardness and wear resistance, making high temperature tempering the only necessary procedure [5, 7].

Based on the performed studies, the paper proposes a method of multilayer surfacing in a nitrogen-containing atmosphere using the R18Yu heat-resistant steel. The method consists in the following sequence of operations:

– preheating of the surfaced workpiece;

– layer surfacing;

– cooling of the surface layer before applying the next one.

Before surfacing of the first layer, the surfaced workpiece is concurrently heated to a $T_{\text{conc}}$ temperature 50–100°C higher than the temperature of the start of martensitic transformation $M_{\text{s}}$. Cooling exposure between surfacing layers is carried out for a time $t_{\text{t}}$ sufficient for the formation of 10–30% martensite. An exposure after the application of each surfacing layer is carried out with a simultaneous decrease in the concurrent heating temperature of the surfaced workpiece $T_{\text{conc}}$ by 20–100°C below the martensitic transformation temperature. After surfacing of the last layer, high-temperature tempering is carried out in a surfacing unit at a $T_{\text{temp}}$ tempering temperature ranging from the recrystallization temperature of the base metal to the temperature of the high-temperature tempering of the surface metal. This method of multilayer surfacing prevents the formation of cracks and increases the hardness of the surface layer up to 59–60 *HRC* [14].

For multilayer surfacing according to the developed technology, PP-R18Yu flux-cored wire was used. The charge of this wire contains carbon, chromium, molybdenum, tungsten, vanadium, aluminum, iron, nickel, and dust obtained from electrostatic precipitators used in aluminum production [17]. In order to improve the quality of the resulting surface layer, titanium was additionally introduced into the charge and chromium was replaced by nitrided ferrochromium.

Replacing chromium with nitrided ferrochrome increases the nitrogen content in the surface metal by 1.5–2.0 times from 0.02–0.04 to 0.06–0.08% during the surfacing in a nitrogen-containing protective alloying medium. The addition of nitrogen to the composition of the surface metal as a strong austenite stabilizer increases the amount of residual austenite and reduces the volume effect of martensite transformation, which reduces the probability of cold cracking. The introduction of nitrided ferrochromium into the charge composition allows the amount of the carbonitride phase to be increased. Obtaining a surface layer of increased hardness and wear resistance is achieved by 3–4-fold high-temperature tempering of residual austenite at 560–580°C. During the tempering process, nitrogen is released from martensite, turning into both cementite carbide and carbides of alloying elements, as well as forming insoluble finely dispersed nitrides and carbonitrides. By increasing the amount of the carbonitride phase and resistance to reversible softening, the nitrogen improves hardness and wear resistance of the surface layer. For the manufacture of a charge of the flux-cored wire, FKhN400A and FKhN600A low-carbon nitrided ferrochrome was used, containing at least 60–65% of chromium and at least 4.0–6.0% of nitrogen (GOST 4757-91).

When titanium is added to the charge [18], an increase in the nitrogen content in the surface metal from 0.06–0.08% to 0.09–0.12% is observed. Therefore, hardness, wear and heat resistance are increased due to the complex alloying of the surface metal with nitrogen during plasma surfacing in a nitrogen-containing shielding-alloying medium, the introduction of nitrided ferrochrome, the presence of aluminum in the flux-cored wire charge, and the additional introduction of titanium into its composition. The introduction of titanium in terms of a strong austenite stabilizer into the composition of the surface metal increases the amount of residual austenite and reduces the volume effect of martensite transformation, which decreases the probability of cold cracking [19, 20].

When titanium is admixed to the charge, the amount of dispersed aluminum and titanium nitrides can be additionally increased. Dispersed aluminum and titanium nitrides, which remain undissolved even at high heating, additionally retard the growth of austenite grains, while increasing the heat resistance of the surface metal. Despite the hardness of the surface metal increasing only by 1–2 *HRC*, a significant increase in wear and heat resistance is established (by 25–50°C). Wear resistance is improved due to an increase in the amount of precipitated hardening phases (titanium nitrides). GOST 4761-91 FTi70 ferrotitanium containing at least 70% titanium was used to manufacture the flux-cored wire charge.

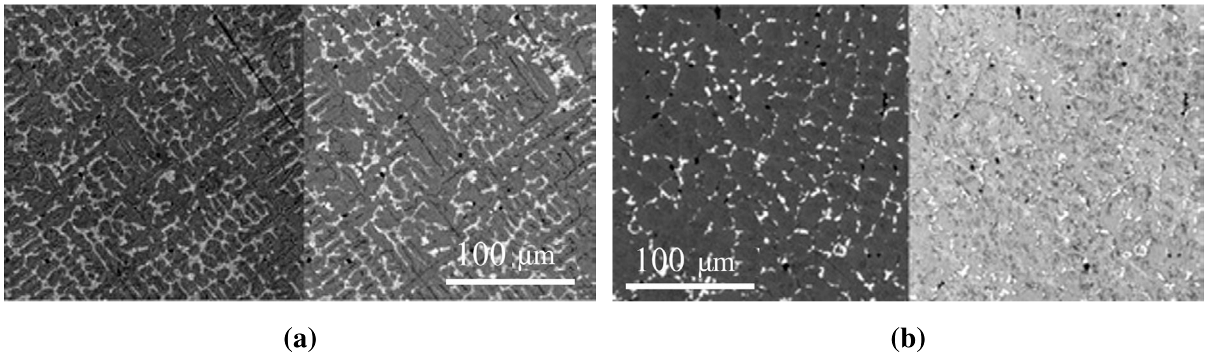



**Fig. 2.** Microstructure of the surface layer made using flux-cored wire based on Al- and N-alloyed R18Yu steel: (a) surface, (b) central zone.

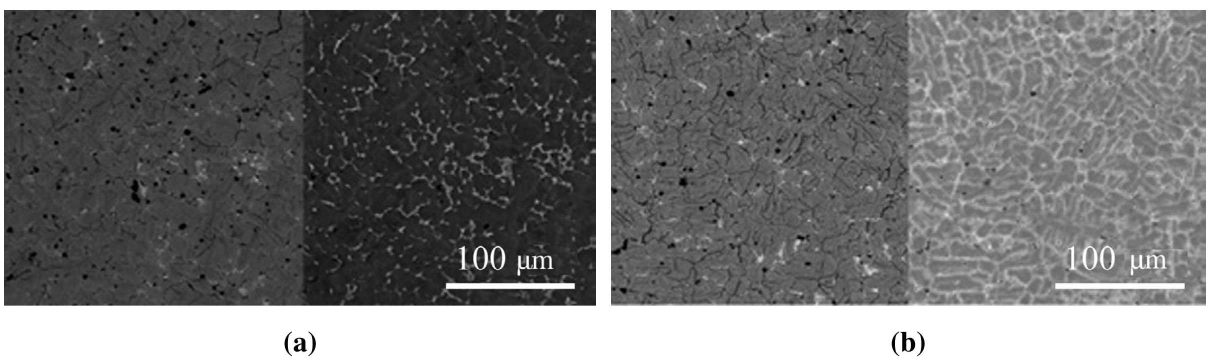
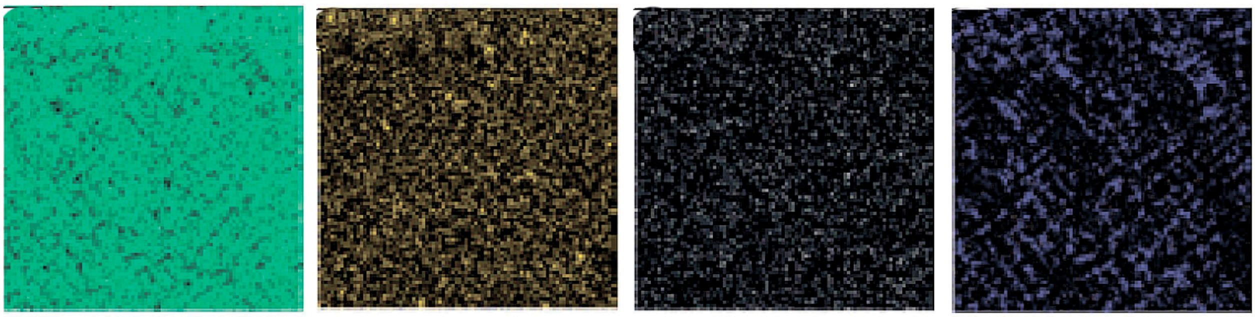



**Fig. 3.** Microstructure of the surface layer made using flux-cored wire based on Al- and N-alloyed R18Yu steel after high-temperature tempering: (a) surface, (b) central zone.

The study of the structural-phase composition of the surface layer by X-ray diffraction analysis (XRD) indicated the presence of $\alpha$-Fe solid solution and compounds based on iron, tungsten, and molybdenum. These compounds are apparently of variable composition, including $Fe_4W_2N$, $FeWN_2$, and $Fe_4W_2C$. All of them have a cubic structure Fd-3m with a crystal lattice parameter of about 11 Å. Al- and Ti-based solid solutions are also present. After surfacing and high-temperature tempering, the main phases include the $\alpha$-Fe solid solution and a complex carbide based on metals of the $Me_6C$ composition. Most likely, the composition of the carbide includes chromium, aluminum, tungsten, and molybdenum. The formula of this carbide is $(Fe,Cr,Al,W)_6C$. This compound also has a cubic Fd-3m structure and a crystal lattice parameter equal to 10.96 Å.

For the obtained samples, metallographic studies were carried out (Figs. 2, 3). The surface layer (see Fig. 2a) has a pronounced oriented dendritic structure. The main part of the material surface is comprised by pearlite grains. Cementite, located at the joints and along grain boundaries, represents iron carbide $Fe_3C$ and compounds based on iron, tungsten, and molybdenum of variable composition $Fe_4W_2N$, $FeWN_2$, and $Fe_4W_2C$. Since the surface metal has a large number of alloying elements, the cementite is most like to have a complex composition of the $(Fe,Cr,Al,Mo,W)_3C$ type. In addition, solid solutions based on aluminum and titanium are detected. Although the central part of the sample (see Fig. 2b) does not differ significantly from the surface morphology, the orientation of the dendritic structure is less pronounced. After surfacing with high-temperature tempering, the oriented dendritic structure is practically invisible. Clearer boundaries of pearlite grains can be observed. The number of complex cementite grains at the grain joints and along their boundaries is significantly lower (see Fig. 3).



(a) (b) (c) (d)

**Fig. 4.** Distribution of elements in the surface layer (surfacing with flux-cored wire based on R18Yu steel) in characteristic radiation: (a) Fe ($K\alpha$), (b) Cr ($K\alpha$), (c) Mo ($L\alpha$), (d) W ($M\alpha$).

EPM studies (Fig. 4) demonstrated a uniform distribution of almost all alloying elements C, N, Al, Si, V, Cr, Fe, Mo, and W in the samples that were surfaced and subsequently tempered at a high temperature, which confirms the assumption of the presence of a $(Fe,Cr,Al,Mo,W)_3C$ cementite type complex composition.

The improved method of multilayer surfacing using flux-cored wire based on the P18Yu steel alloyed by aluminum, titanium, and nitrogen, presented in this article, was applied to manufacture working and toothed rolls of a GUNDLACH 3030S crusher. The operation of the rolls in production conditions proved an increase in their wear resistance by 1.5–2.0 times in comparison with the standard rolls supplied with the equipment.

## CONCLUSIONS

1. During the surfacing carried out using wire made of 3Kh2V8, 4Kh4V10Yu, and R18Yu steels, the lowest residual stresses of 120–130 MPa were shown to be produced by R18Yu-based wire.

2. The improved method of multilayer plasma surfacing by heat-resistant steels under a nitrogen atmosphere is presented as preventing the crack formation and increasing the hardness of the surface metal up to 59–60 *HRC* without subsequent heat treatment.

3. The addition of nitrided ferrochromium and titanium to the R18Yu-based flux-cored wire provides an increase in the hardness, wear and heat resistance of the surface layer.

Based on the results of the study, multilayer surfacing, together with the addition of ferrochromium and titanium to the surfacing wire, can be used to obtain a metal not prone to cracking and in a state close to that of a hardened metal.

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