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Steel surface strenghtening by overlay welding and plastic deformation

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1. Introduction

In most cases parts are overlay welded to obtain high alloyed coatings for the increasing of wear resistance and other properties. Chemical composition of steel can be modified adding some alloying elements such as Cr, Ni, Mn, Si, W and others, which form hard carbides or joint intermetallic compounds required for precipitation hardening [1].

The precipitation hardened steels provided with good mechanical properties have high strength and suitable plasticity after aging [2, 3]. Hardness of steel which consists of wt., %: 0.01 C; 17.86 Ni; 9.41 Co; 4.84 Mo; 0.76 Ti; 0.14 Al after heating at the temperature of 900°C followed by cooling in the air, and aging at 480°C for 15 hours increases from 320 HV up to 640 HV. Furthermore, it was observed that steel haven't softened on the increasing aging time up to 25 hours. It was found that hardness of steel 18Ni-Co-Mo-Ti aged in temperatures higher than 510°C was lower due to the presence of high amount of austenite.

In the early 1960s the precipitation hardened steels have found a wide range of applications. In practice, engineers and technicians often have to deal with residual stresses occurring after different machining and heat-treatment processes [4, 5].

The precipitation hardening of high alloyed steels is relatively expensive process to produce parts [6]. It is cost-effective to produce parts from cheap structural steel subjected to overlay welding and covered with the layer of precipitation hardened steel. Various powder wires and powder mixtures with additive materials can be used to obtain high alloyed coatings employing the most popular welding techniques, such as metal-inert gas (MIG), tungsten-inert gas (TIG), manual metal arc (MMA), submerged arc welding (SAW) and etc.

Hardfacing is the most popular and cost effective method to improve wear resistance of the parts, tools and etc. In the work [7] carbon steel were deposited by gas Ar+CO_2 shielded arc welding process with powder wire to estimate the effect of welding procedure on coating structure and properties. Obtained coatings consist of wt., %: 0.40–0.48 C; 1.1–1.3 Mn; 0.49–0.60 Si; 5.3–5.5 Cr; 2.3–2.6 Mo; 0.34–0.40 V; 1.8–1.9 W. Gas mixture consisting up to 20% CO_2 showed a small effect on the weld deposit chemistry. Welding with high heat input resulted in larger carbides precipitation, a reduction in the retained austenite content and lower hardness when aging at 550°C. The welded specimens with the lower heat input and gas shielding with low CO_2 content exhibited the highest alloy content, the highest proportions of retained austenite and highest hardness.

Plastic deformation has become an effective method to strengthen steel surface. The tested alloy (1.2% C, 12.86% Mn, and 0.87% Si) were heated at the temperature of 1050°C for 2 h, and then water quenched. After the heat treatment the investigated alloy exhibited a single austenite phase, with grain sizes approximately 100–200 μm. Test samples were subjected to shot peening by cast steel balls (0.2 mm nominal diameter). After the shot peening process were obtained a nanocrystalline surface layer. The grain sizes in the superficies layer varied in the 11.1–17.4 nm range, hardness increased from 256 HV to 774 HV. The wear resistance of treated surfaces increased in 72% for 30 min peening duration [8].

A special heat treatment followed by sufficient rapid cooling of the material allows storing austenitic structure, which is stable at the room temperature. Certain amounts of alloying elements permit adjusting the stability of the retained austenite to metastable state. The high alloyed steels X210Cr12 (AISI D3) and X155CrMo12-1 (AISI D2) consisting up to 2% of carbon and up to 13% Cr were heat treated to obtain a structure with a high content of retained austenite. The work pieces (60 mm diameter) were turned and subsequently deep rolled using a 6 mm diameter ceramic ball. Hardness of the machined surface in the turning process increase up to 700 HV, the depth of hardened zone is 0.2 mm. After the deep rolling hardness of the workpiece increase up to 810 HV [9].

Increasing the strength of steel by cold-working can be due to the strain, phase transformation, grain refinement and precipitation strengthening. The yield strength of the aged steel (wt., %: 0.041 C; 1.473 Mn; 0.32 Mo; 0.02 Ti; 0.023 Al) at 400°C for 30 min increases from 470 MPa to 614 MPa after 20% cold working [10].

Stainless maraging steels of type PH13-8Mo are used for components in aircraft industry, for plastic mould dies and for sports industry because of their corrosion resistance and excellent combination of strength and ductility [11]. Effect of aging for 100 hours at the temperature of 525°C on mechanical properties of Ti-containing (wt.,%: 13 Cr; 8.3 Ni; 1.1 Si; 1 Ti; 1.2 Al; 0.6 Mo; 0.1 Mn; 0.05 C;) and Ti-free (wt., %: 12.8 Cr; 8.6 Ni; 0.6 Si; 3.4 Al; 0.8 Mo; 0.4 Mn; 0.1 C;) steels type PH13-8Mo were investigated.

Aging was performed at the temperature of 850°C or 1000°C followed by air cooling. A Ti-free alloy contained approximately 2% of retained austenite after the heating it at 850°C and during aging at 525°C, the amount of retained austenite increased to a value that is twice higher. A Ti-containing alloy is free of retained austenite after the heating it at 1000°C followed by air cooling. Aging at 525°C leads to the formation of retained austenite (2%) after the aging time of 10 h. The higher hardness and maximum strength for both materials is fixed after aging for 3 h at 525°C. Longer aging results in lower strength. Aged for 3 h Ti-free alloy exhibits the increase in hardness from 34 HRC to 51 HRC and in tensile strength from 1115 MPa to 1751 MPa. An embrittlement found for the Ti-containing alloy in the early stages of aging through segregation of impurity or alloying elements to grain boundaries and preferential precipitation of the second phase along grain boundaries [11].

Structural steel St 44-3 (DIN 17100) (0.15% C) was used as the parent material for surfacing. Surfacing was carried out with four differently alloyed Ni–Co–Mo alloys, related to the commercial maraging steels of Ni–Co–Mo type. The coatings were alloyed with Ni, Co, Mo, Ti, and Al. The relevant temperature/time conditions of precipitation annealing of the surfaced specimens was chosen to obtain the highest hardness. The higher hardness (up to 58 HRC) after aging for 7–35 h at 450–460°C was obtained for the coatings consisting of wt,%: 10.5–13 Ni; 9.5–13 Co; 8.5–11 Mo; 0.7–1.5 Ti; 0.04–0.16 Al; 1.4–1.6 Si [12].

The aim of this work was to obtain alloyed coatings by overlay welding of structural steel, investigate the effect of heat treatment, and applied plastic deformation on coating properties and structure.

2. Materials and methods

A wide variety of welding techniques are used in order to obtain coatings with different composition and structure for built up layers or for manufacturing of new parts and tools. The overlay welding, the simple and low cost method, can be applied for a new part being produced in order to reach desirable wear properties and/or dimensions. It is cost-effective to produce parts from cheap structural steel subjected to overlay welding and coated with alloyed steel layer.

The structural steel Ст3 (GOST 380–88) (wt., %: 0.14 – 0.22 C; 0.12 – 0.3 Si; 0.40 – 0.65 Mn) was selected for overlay welding. Surface of structural steel was cladded with the layer of powder sprayed over or bounded with surface and fused by electric arc struck between the continuously supplied 1.2 mm diameter low carbon steel wire Св 08 (< 0.1%C) (GOST 2246) under the flux ОСЦ 45 (GOST 9087–81) (the main components are SiO_2 and MnO) and without standard flux and substrate (Table 1). Specimens were overlay welded in the device, assembled from the lathe and semiautomatic machine INTEGRA 350 Professional with welding burner MIG/MAG EN 500 78. Welding parameters: current I = 180-200 A; voltage U = = 22-26 V; welding travel speed $V_{welding}$ = 14.4 m/h; wire feeding rate V_{wire} = 25.2 m/h.

For the overlay welding process the powder were prepared from standard and utilized waste materials. In the study [13] milling of hardmetal plates and powder preparation processes, which may be applied for the thermal spraying, was investigated. Investigation to use bearing steel grinding waste for electric welding was reported in [14].

Drills milling chips of P6M5 (GOST 19265 – 73) steel are brittle that causes the easy milling process. The waste was heated up to 350°C temperature seeking to remove lubricant–coolant fluid. In such a way waste material was obtained. P6M5 steel chips during welding process are melted and the weld become rich in tungsten, molybdenum and other elements which present in chips.

Stainless steel (18% Cr, 20% Ni) and titanium milling chips are ductile therefore it is difficult to crush them into powder, that's why it were heat treated in the electrical furnace without protected gas. The stainless steel chips were heated for 5 hours at 1100°C and titanium chips for 2 hours at 950°C respectively were oxidized therefore facilitate the milling process.

X-ray diffraction showed that the heat treated stainless steel chips contain Fe-Ni and Cr oxides and the dominating component in the titanium chips – rutile (TiO_2). In the arc burning zone during the metallurgical reaction processes coating was enriched in Ni, Cr and Ti.

Powders obtained after crushing of BK-8 plates consist of 92% tungsten carbide and 8% cobalt. After the milling of grinding disks were obtained WC powders consist of silicon carbide and low amount of ceramic binder as a result obtained coting possessed higher amounts of silicon and carbon. Silicon acted as deoxidizer and certain amount of it passes to the overlay welded layer.

The flux for the submerged arc welding (SAW) of steel had typical chemical composition in which the main component was SiO_2. Glass powder was applied for the overlaying instead of conventional flux. Glass component SiO_2 deoxidized weld metal and alloyed it by silicon [15].

Metallurgical industrial powders – Cr, Fe-70% Mn, Ni, Al_2O_3, Cr-Ni were added into mixture subjected to overlaying to obtain high alloyed coatings. Powder composition, wt., %: 13 Cr; 73.4 Ni; 3 B; 4 Fe-Cr-Ni; 4 Si; 2 Cu; 0.6 C.

The examination of microstructures was executed with microscopes LMA 10 and Carl Zeiss Axio Scope A1. Magnification range of 100–350 times was used for revealing of phases.

The phase compositions of overlay welded coatings were analysed by X-ray diffraction patterns registered by diffractometer DRON-6, the X-ray tube voltage Ua = = 35 kV, current Ia = 20 mA.

The hardness HRC values of overlay welded coatings were tested on Rockwell's hardness testing machine TK–2 using a 1470 N load and a diamond indenter shaped in the form of a conus with angle 120°.

Micro hardness was tested using ПМТ–3 microhardmeter with an applied load of 0.49 N, 0.98 N, 1.96 N and a 136° diamond pyramid indenter.

3. Results and discussion

The surface of coatings made of structural steel Ст3 was applied to 4 mm thickness of a powder mixed with 10% of liquid glass (Table). Coatings were heated for 3 hours at the temperature of 250°C. Evaporated water caused the powder mixture to adhere to the metal base.

All the components were melted by arc struck of continuously supplied low carbon steel wire. Hardness of obtained overlay welded layer was low (not exceeded 28 HRC, Fig. 1). Maximum hardening was stated at 650°C after the heat treatment of coatings at 500–750°C for 1 hour. Hardness increase up to 27–35 HRC. The heat treatment temperature and duration influenced the hardness of coatings (Fig. 2). Higher quantity of austenite stabilizing elements (Cr, Mn, Ni) and presence of high amount of retained austenite elements caused low hardness of layer. After the etching of the overlay welded coatings using 3% Nital solution reveals dendrites consisting of retained austenite (Fig. 3, a).

Table

Composition of powder mixture

Specimen No.	Composition of powder mixture, %							
	P6M5	SiC	Fe–70% Mn	Ni	Oxidized Ti chips (TiO_2)	Cr	Cr–Ni	Al_2O_3
1	30	20	10	10		20		10
2	20	20	10		10	20	20	

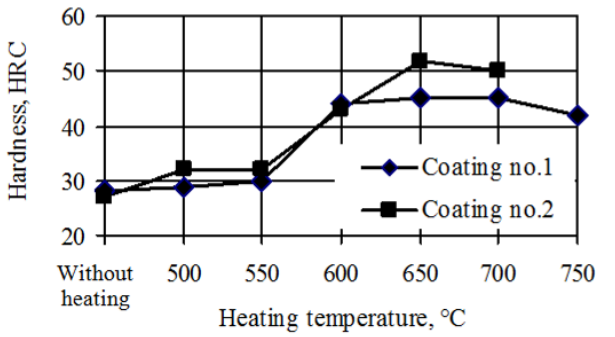


Fig. 1 Effect of heating temperature to the hardness of overlay welded layers

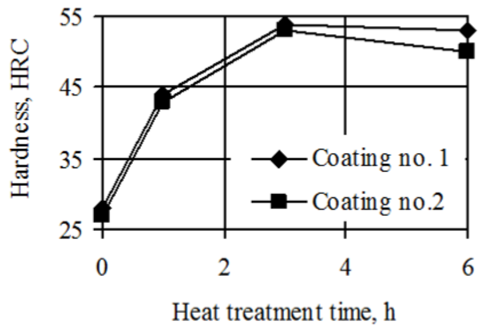
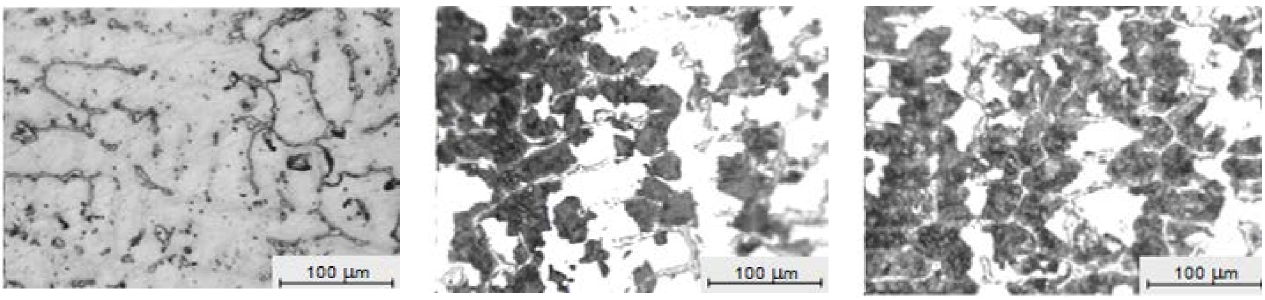


Fig. 2 Effect of heat treatment duration at 600°C to the hardness



a b c

Fig. 3 Microstructures of coatings obtained by overlay welding of steel with powder mixtures (Coating No. 2 in Table 1) and melted by arc: a – without heating, b – 600°C, 3 h, c – 600°C, 6 h

X-ray diffraction patterns (Fig. 4, a) cleared presence of high amount of retained austenite, extremely the Fe_{γ} peak is the most intensive (diffraction angle 2θ~50°). The heat treated coating for 3 hours at 600°C temperature presents the visibly less amount of retained austenite (Fig. 4, b) – Fe_{α} peak (diffraction angle 2θ~45°). There is no Fe_{γ} peak in X-ray diffraction of coating treated at 600°C for 6 hours.

The higher hardness (54 HRC) of coatings was fixed after the heat treatment at 600°C for 3 hours. Longer duration of process results in lower hardness. The higher hardness (52 HRC) was achieved for the coatings heat treated at 650°C for 1 hour. Hardness decreased in 7 HRC with increasing duration of process till 3 h. Variation of hardness was induced by retained austenite transformation to martensite and age hardening. Similar processes can be observed in the maraging martensitic steels.

Maraging steels have a Cr content higher than 12% and show excellent combination of high strength and ductility. A noticeable feature of those maraging steels is a good combination of high strength and toughness, which is achieved by the formation of uniformly dispersed intermetallic phases in a Ni-rich martensitic matrix. The most relevant elements for forming intermetallic phases in maraging steels are Ni, Al and Ti [16]. Hardness of steels (wt., %: 0.12 C, 12-13 Cr, 8-9 Ni, 0.5-0.8 Mo, 1.0-3.4 Al, up to 0.6 Ti) increases from 28-34 HRC up to 49-51 HRC after ageing for 5 h at 520°C temperature.

The excellent mechanical properties of steels (C~0.4%) are essentially due to negligible additions of alloying elements: Mn, Mo, Ti, Al, Nb with applying of deformation and ageing [10]. Alloying elements, deformation rate, ageing temperature and duration has effect on mechanical properties. Steels may strengthen due to the strains by applied deformations, phase transformation, grain refinement and precipitate hardening.

The surface of coating No. 2 (Table) was deformed by hammering it with rounded tool. After the deformation the hardness increase from 27 up to 52 HRC. During deformation, the strengthening of surface was provided by the transformation of retained austenite to martensite. It is shown on the X-ray diffraction patterns (Fig. 4, d) scanned from deformed (no etched) and etched (etching depth 0.3 mm) surfaces. More martensite (Fe_{α}) presented in the no etched surface than in the partially etched of deformed surface.

In some cases steel is overlay welded to form the intermediate layer, which serves as a reduction in changes of properties between the base metal and coating.

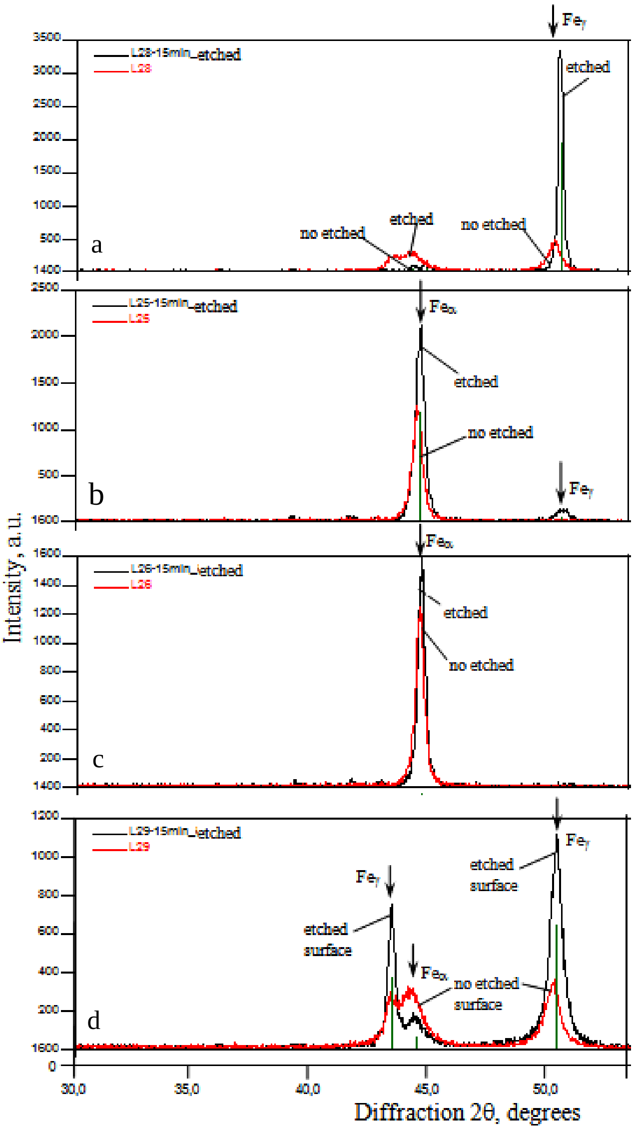


Fig. 4 X-ray diffraction patterns of coatings obtained by overlay welding of steel with powder mixtures (20% P6M5, 20% SiC, 10% Fe–70% Mn, 10% TiO_2, 20% Cr, 20% Cr–Ni) and melted by arc: a – without heat treatment, b – 600°C, 3 h, c – 600°C, 6 h, d – deformed surface

To form substrate the powder of oxidized titanium chips (5 g TiO_2) were spread over the structural steel Ст3 (10x100 mm) surface and melted by wire Св 08 arc under the milled glass layer. Coating were overlay welded with powder mixture consisting of wt., %: P6M5–28, SiC–18, Fe–70% Mn–9, oxidized stainless steel chips–9, Cr–20, Al_2O_3–8, liquid glass–8. Powder was bond with liquid glass and heated for 3 hours at 250°C after that obtained adhered body was milled, spread on the base and melted without standard flux. During the overlaying process, melted powder mixture contact with substrate containing of titanium therefore the coating was alloyed additionally by titanium. Hardness of overlay welded layer was 35 HRC. After heating for 3 hours at 600°C temperature hardness increase up to 56 HRC. Fig. 5 shows microhardness range of the coating layer depth.

On analysing results hardness variation in the overlay welded layer was observed. The higher hardness was noted in the fusion interface between substrate and coating due to presence of less amount of retained austenite (Fig. 6, a). After etching with 3% HNO_3 was observed the formation of dendrites bright zones due to presence of retained austenite. Fig. 6, b exhibits the microstructure of the substrate in which seen bright ferrite grain. The hardness of coating increase after the heating it for 3 hours at 600°C temperature but hardness of substrate almost does not change.

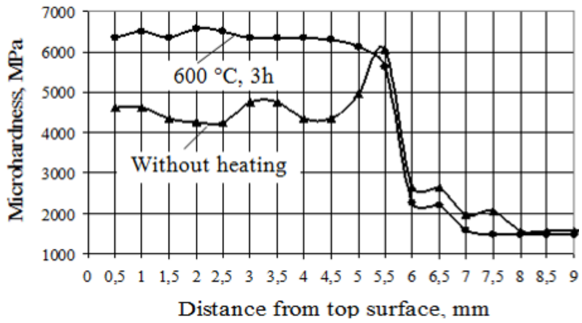
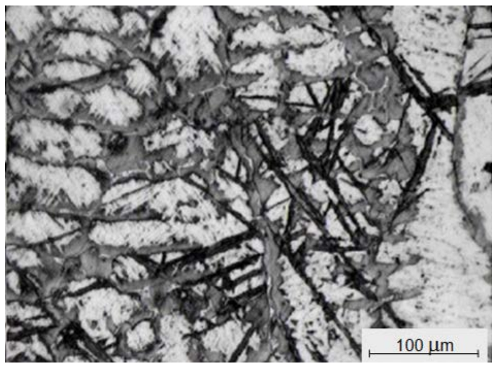
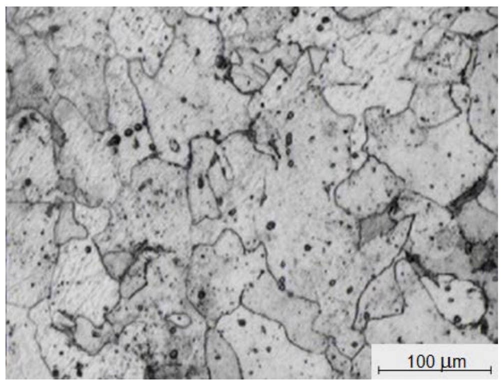


Fig. 5 Microhardness of the coating layer depth



a



b

Fig. 6 Microstructures of coating (a) and substrate (b)

The coating surface was plastically deformed by hammering it with rounded tool. After the deformation the hardness increase up to 56 HRC. Heating at 600°C temperature has no effect on hardness of strengthened coating.

4. Conclusions

1. Overlay welding of the structural steel Ст3 using the waste materials, such as milled grinding disks (SiC), glass, high speed tool steel P6M5, worn grinding disks, hard metal plates and titanium chips enabling to obtain coatings alloyed by tungsten, silicon, molybdenum, nickel, chromium, titanium and other elements required

for precipitate hardening during heat treatment process.

2. The higher hardness (from 28 up to 52 HRC) was fixed at 650°C temperature when overlay welded with mixture, consisting powder of high speed steel and oxidized titanium chips, milled grinding disks (SiC), coatings were heated for 1 hour at 500°C – 750°C temperatures. The longer holding duration at the same temperature causes the decrease of coatings hardness. Hardness increased from 28 HRC up to 43 HRC after heat treatment for 1 hour at 600°C temperature, after the increasing holding duration for 3 hours – up to 54 HRC. Longer holding duration results decrease in surface hardness.

3. Plastically deformation of alloyed and consisting high amount of retained austenite coating by hammering it with rounded tool provide increases of hardness from 27 up to 52 HRC. Hardness of plastically deformed coating after heat treatment can be increased only several HRC units (up to 5 HRC).

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STEEL SURFACE STRENGHTENING BY OVERLAY WELDING AND PLASTIC DEFORMATION

S u m m a r y

A study of this work was to overlay welding of structural steel by automatic submerge arc welding process with mixtures, consisting powder of high speed steel P6M5 and oxidized titanium chips, milled grinding disks (SiC). Powder of waste materials mixed with manufacturing powder consist of Mn, Cr, Ni, Al and other elements were bounded with liquid glass to the base metal and melted by arc struck between continuously supplied low carbon steel wire Cв 08 (<0.1% C, 1.2 mm diameter) under the flux ОСЦ 45.

Maximum hardening was fixed at 650°C after the heat treatment of coatings at 500-750°C for 1 hour. The higher hardness (54 HRC) was obtained at 600°C temperature after the heating for 3 hours and after the plastically deformation – from 27 HRC up to 52 HRC.

The structure and properties of coatings were investigated by metallographic and X-ray diffraction methods, by measured hardness and microhardness.

Keywords: overlay welding, coating, powder, hardness.

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