EDDY CURRENT QUALITY CONTROL OF NICKEL-CHROMIUM COATINGS FORMING IN THE PROCESS OF GAS-POWDER LASER CLADDING AND SUBSEQUENT STABILIZING ANNEALING

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Introduction

Gas-powder laser clad coating is an effective method of formation of wear-resistant coatings on the metal products surface [1, 2]. Until very recently, coatings on the base of nickel [3, 4] and cobalt [5, 6], hardened by chromium, tungsten and cobalt carbides and borides, continue to attract special attention of researchers. The most optimal use of modern hardening technologies is provided by application of nondestructive method of quality control of formed surface layers, as well as by forecasting of their workability in different conditions of mechanical and thermal action. Development of physical evaluation method of residual life of steel products with clad wear-resistant coatings, subjected to friction and abrasive action in service conditions, is of considerable practical interest.

As applied to products, processed by laser radiation, the use of physical methods is often oriented to hardened layer depth control [7, 8]. In [9-11] electromagnetic method was also used for evaluation of structural state, hardness and wear resistance of constructional and high-carbon steel, subjected to laser quenching and subsequent thermal action.

In this research, the possibilities of eddy-current method for testing of hardness and wear resistance under abrasive wear and sliding friction of laser clad Cr-Ni and Cr-Ni-Co coatings, widely applied for reconstruction of rapid-wearing machine parts, are investigated. Eddy-current method was also used for thickness evaluation of coatings, formed during laser quenching and subsequent grinding of flowed surface, as well as coatings kept after abrasive wear of surface layer.

Powders of PGSR-1, PG-10N-01 and PG-10K-01 grades (Table 1) was served as material for coatings. Structure, chemical composition and microhardness of the coatings was investigated with application of scanning electron microscope Tescan VEGA II XMU, wave-dispersive (Inca Wave 700) and energy-dispersive (INCA Energy 450 XT) microanalyzers as well as Leica VMHT hardness tester. Change of structure, microhardness and chemical composition in depth of laser affected area was examined on transversal metallographic sections. Phase composition of the coatings was defined using X-ray diffractometer SHIMADZU XRD-7000.

Table 1. Chemical composition of the powders

Powder grade	Element content, wt. %							
	C	Cr	Ni	Co	Fe	W	Si	B
PGSR-1	0.3	13.5	Balance	-	<5.0	-	2.4	2.7
PG-10N-01	0.8	16.0	Balance	-	<5.0	-	4.0	3.5
PG-10K-01	1.5	23.0	29.1	Balance	2.5	4.0	1.2	1.6

Intensity of abrasive wear in depth of coatings was defined during the progress of repeated test, resulting in consequent removal (wearing out) of surface layer. The tests was carried out upon sliding of end surfaces (7×7 mm) of clad samples over fixed abrasive – corundum and silicon carbide with approx. 160 μm grain. The tests of end surface (7×7 mm) of clad samples upon sliding friction conditions was accomplished in the air, in pair with Kh12M steel plate having hardness 58-59 HRC_{eq}. For each individual abrasive wear test and sliding friction test, the wear intensity was calculated by formula $Ih=Q/qSL$, where Q is the sample weight loss, g; q is the density of the sample material, g/sm^3; S – geometric contact area, sm^2; L is the single test slip distance, sm.

Measurements of electromagnetic parameters was carried out with a laboratory prototype of an eddy-current instrument using differentially connected attachable transformer transducers with

pot core at frequencies of f=2.4, 24, 72, 96 and 120 kHz. Eddy-current transducer with flat end surface and testing locality about 5-6 mm in diameter was applied [10] which allows to perform measurements at the end surfaces of specimens (7×7 mm) without any influence of the edge effect. At that the change of eddy-current characteristics in depth of clad coatings was determined by layer-by-layer grinding off of surface layer. Rated depth of electromagnetic field penetration into metal sample (under **e**-fold field weakening) was evaluated by formula $\delta = 503\sqrt{\rho / \mu_{init} f}$, where ρ is the electrical resistivity, μ_{init} is the initial permeability.

Results

As a result of double-layer laser cladding, coatings of 1.2-1.6 mm in thickness were formed at the surface of St3 steel. The coatings are characterized sufficiently uniform distribution of structural constituent throughout the thickness (Fig. 1). The coatings has dendritic structure and the direction of dendrites is in conformity with temperature gradient during crystallization. Dendrites of PGSR-1 and PG-10N-01 Cr-Ni coatings consist of γ-solid solution on the base of nickel (Table 2). Interdendritic intervals represent eutectic consisting of nickel and small amounts of silicon and boron. According to X-ray structural analysis data, the basic strengthening phases of Cr-Ni coatings are chromium carbides and borides of CrB type. Carbide phase of PGSR-1 coating is represented with dispersive $Cr_{23}C_6$ particles. The PG-10N-01 coating additionally has the Cr_7C_3 particles (see Table 2) because of higher carbon content (see table 1). The base of Cr-Ni-Co coating constitutes α-(Co-Ni) solid solution, and the main strengthening phases of considered tungsten-containing clad coating are Cr_7C_3, CrB, WC and WB (see table 2).
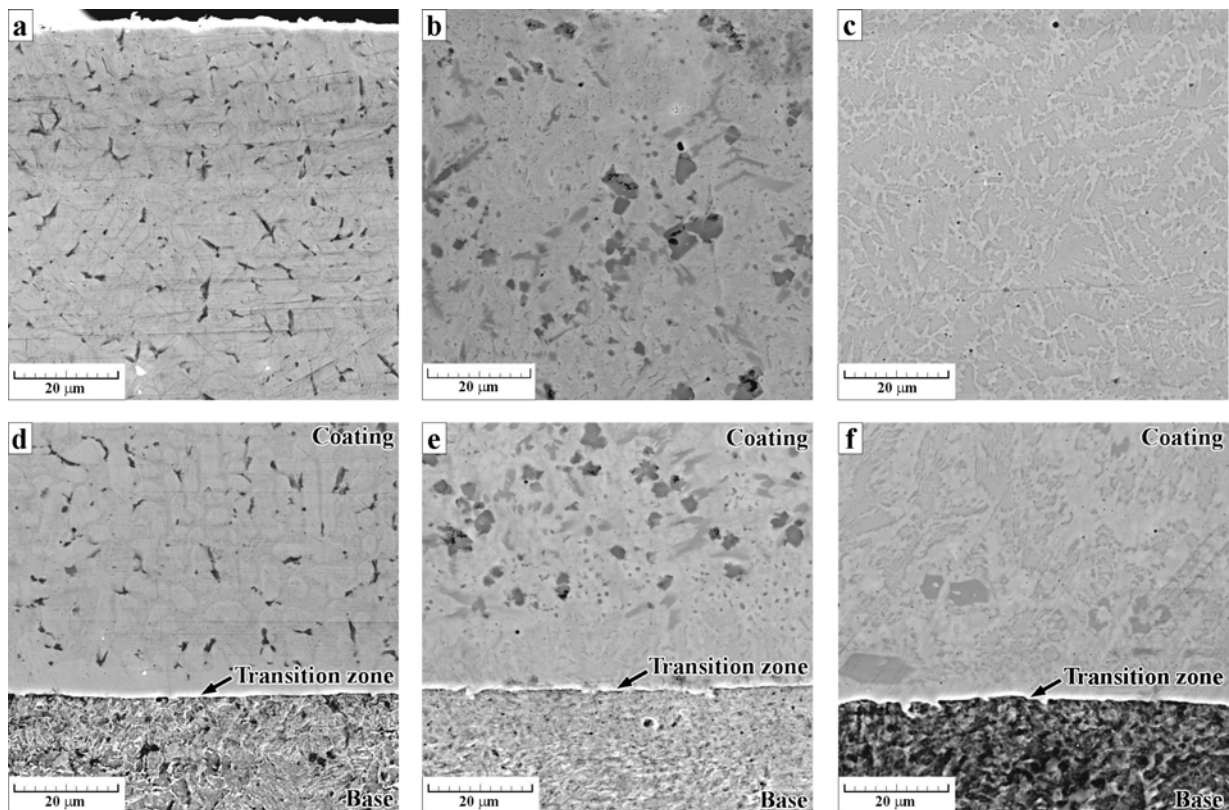

Fig. 1. Microstructure of PGSR-1 (a, d), PG-10N-01 (b, e) и PG-10K-01 (c, f) coatings in the vicinity of surface (a-c) and at the boundary with base (d-f).

Quantitative X-ray spectrum analysis showed, that average chemical composition of the coatings is close to composition of powders for cladding (see Table 1). In transition zone (approx. 5-20 μm in thickness) from coating to base the interfusion of coating and base material occurs: nickel, chromium and silicon content decreases, iron content increases (Fig. 2).

Table 2. Structural and physico-mechanical characteristics of the coatings of different kinds

Coating characteristic	Coating		
	PGSR-1	PG-10N-01	PG-10K-01
Master phase	$\gamma-Ni$	$\gamma-Ni$	$\alpha-(Co-Ni)$
Main strengthening phases	$Cr_{23}C_6$, CrB	Cr_7C_3, CrB, $Cr_{23}C_6$	Cr_7C_3, CrB, WC, WB
Average microhardness, GPa	5.3	8.5	7.4
Mean wear intensity under abrasive wear over corundum	$1.7 \cdot 10^{-5}$	$0.6 \cdot 10^{-5}$	$0.9 \cdot 10^{-5}$
Mean wear intensity under abrasive wear over silicon carbide	$1.8 \cdot 10^{-5}$	$1.3 \cdot 10^{-5}$	$1.1 \cdot 10^{-5}$
Wear intensity under sliding friction upon steel in air	$8.9 \cdot 10^{-8}$	$4.4 \cdot 10^{-8}$	$3.1 \cdot 10^{-8}$
Wear intensity under sliding friction upon steel in argon	$8.5 \cdot 10^{-8}$	$0.5 \cdot 10^{-8}$	$0.4 \cdot 10^{-8}$
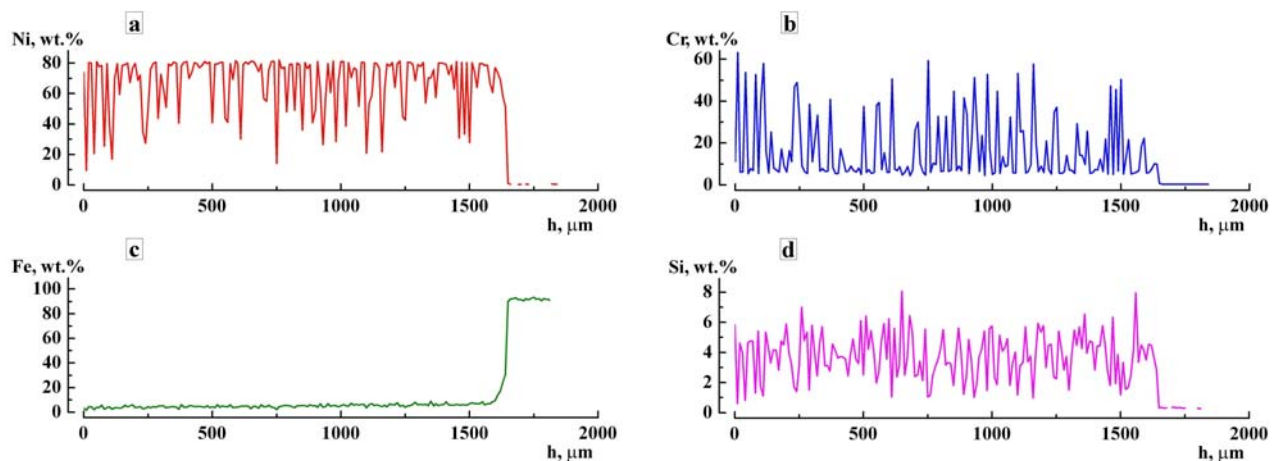
Fig. 2. Distribution of chemical elements throughout the thickness of PG-10N-01 coating.

In Fig. 3 changes in the mechanical and electromagnetic parameters in depth of coatings under consideration are represented. It can be seen that the coatings have almost constant microhardness and intensity of abrasive wear throughout the whole thickness of clad layer. Strong growth of abrasive wear intensity and the decrease of hardness take place in transition zone - in transition from coating material to steel base. It follows from Fig. 3 and Table 2 that PG-10N-01 coating is characterized by elevated microhardness (6.8-9.7 GPa) in comparison with PGSR-1 coating (4.3-5.7 GPa), as well as lower level of wear intensity (elevated wear resistance) under abrasive action and sliding friction upon steel plate.

The PG-10K-01 coating is intermediate by hardness and wear resistance in abrasive testing over corundum between PGSR-1 и PG-10N-01 coatings (see Fig. 3, Table 2). However, in abrasive testing over silicon carbide the minimal wear intensity of PG-10K-01 coating can be noted, which is lower even in comparison with PG-10N-01 coating, having maximal average hardness among all considered clad coatings.

Table 3 shows for the three laser clad coatings the result of eddy current measurements carried out with one setup of eddy current instrument specific for each of used electromagnetic field excitation frequency. It can be seen, that eddy current characteristics of PGSR-1 and PG-10N-01 clad coatings, differing with chemical and phase composition, hardness, wear resistance (see Table. 1, 2; Fig. 3), are also essentially different. At that the difference in value of informative signal of eddy current transducers for Cr-Ni clad coatings increases as frequency f decreases. For Cr-Ni-Co

PG-10K-01 coating the lower readings of eddy current instrument are characteristic in comparison with Cr-Ni coatings (see Table 3).
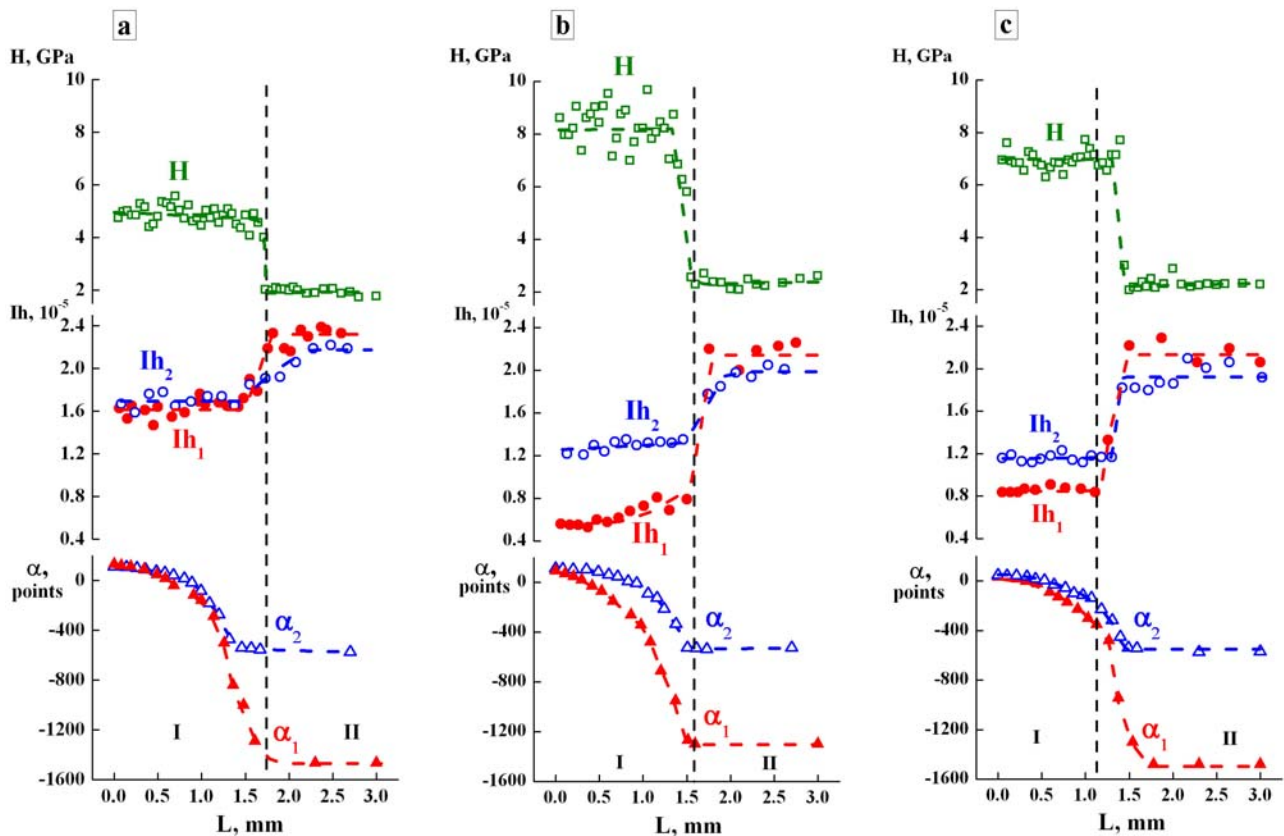

Fig. 3. Cange of microhardness H, wear intensity (in wear testing over corundum Ih_1 and silicon carbide Ih_2) and readings of eddy current instrument α_1 (frequency f=2.4 kHz) and α_2 (frequency f=72 kHz) in depth of surface layer with clad coatings:
a – PGSR-1; b – PG-10N-01; c – PG-10K-01

Table 3. Eddy-current characteristics of the coated samples measured for the different frequencies f

Coating	Readings of the eddy-current instrument α (points)				
	f=2,4 kHz	f=24 kHz	f=72 kHz	f=96 kHz	f=120 kHz
PGSR-1	100	91	99	94	92
PG-10N-01	61	63	73	79	80
PG-10K-01	7	4	17	17	17

Fig. 3 describes variation of readings of eddy current instrument in depth of clad layers. In this experiment (in contrast to measurement, represented in Table 3) the various eddy current setup sensitivity tunings were used for different clad coatings. It can be seen that eddy current characteristics of Cr-Ni and Cr-Ni-Co coatings differ hundred times from of St3 steel base ones. When approaching to ferromagnetic base the readings of eddy current instrument α decrease due to ever-increasing influence of steel base. Descent rate of readings of eddy current instrument in depth of surface layer increase noticeably by decrease of used electromagnetic field frequency from f=72 kHz (see Fig. 3, α_2) to f=2.4 kHz (see Fig. 3, α_1). Consequently, in measurements on small frequencies (and, correspondingly, in greater electromagnetic field penetration depth), eddy current method sensibility to depth change of coatings rises.

In Fig. 4 signal dependencies of eddy current transducer α on Cr-Ni and Cr-Ni-Co coatings depth are presented. It can be seen that value α increases continuously with increase of coating thickness for all kinds of laser clad coating. It is caused by reduction of initial magnetic

permeability of analyzed layer as far as the influence of ferromagnetic steel sample base on measured electromagnetic characteristics decreases.
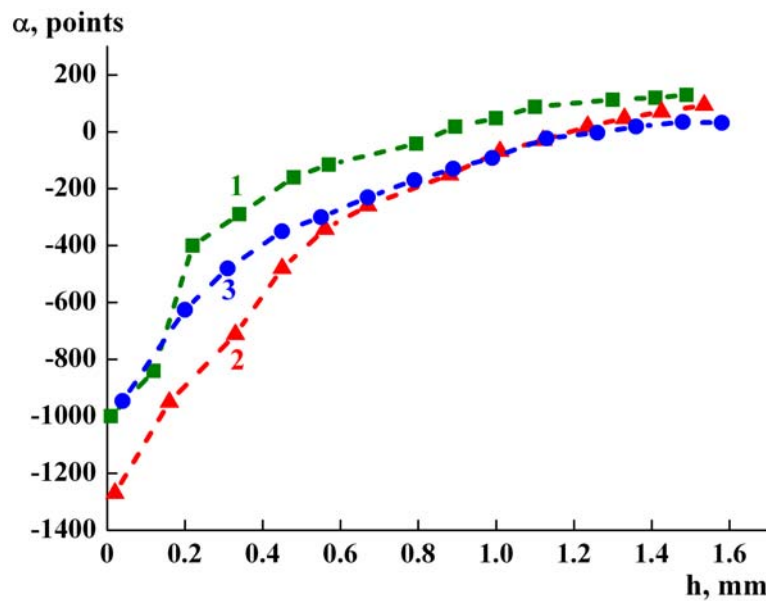

Fig. 4. The influence of coating thickness h on readings of eddy current instrument α (frequency f=2.4 kHz): 1 - PGSR-1; 2 - PG-10N-01; 3 - PG-10K-01.

Discussion

The constancy of microhardness and abrasive wear intensity throughout the whole thickness of clad layer (see Fig. 3) reflects relatively uniform distribution of structural constituents in depth of coatings (see Fig. 1, 2). Drastic growth of abrasive wear intensity and drop of hardness in transition zone (see Fig. 3) corresponds to sharp change of structure and chemical composition in transition from coating material to steel base (see Fig. 1, 2).

The observed higher levels of microhardness and wear resistance of PG-10N-01 coating in comparison with PGSR-1 coatings (see Fg. 3 and Table 2) are caused by the presence in PG-10N-01 coating of larger fraction of hardening carbide and boride phases, in particular Cr_7C_3 carbide, which is considerably stronger than $Cr_{23}C_6$ carbide being the base carbide phase in PGSR-1 coating.

Let us consider the wear features of investigated coatings. It is important to note that if close levels of abrasive wear in wear tests over corundum and silicon carbide are observed in PGSR-1 coatings (see Fig. 3a, Table 2), in more high-strength PG-10N-01 coating the wear intensity under wear over corundum is significantly lower (by a factor of 2.2) than under wear over silicon carbide (see Fig. 3b, Table 2). The last is caused by irregularity of microcutting mechanism in case of sliding of PG-10N-01 coating upon electrocorundum because microhardness of Cr_7C_3 carbides (as microdurometerical measurements showed, H=16.2-19.3 GPa), present in this coating, is close to corundum microhardness. In PGSR-1 coating $Cr_{23}C_6$ carbide phase (as of microhardness measurements H=9.9-11.3 GPa) significantly inferior to corundum in microhardness and therefore don't preclude of microcutting occurence. In wear tests over silicon carbide, which hardness (H about 30 GPa) excels significantly the hardness of all basic phases consisting Cr-Ni coatings, wearing of both coatings proceeds by a mechanism of microcutting. Noted for PG-10K-01 coating minimal wear intensity in wear tests over silicon carbide is caused by the present of tungsten boride WB (see Table 2) in PG-10K-01 tungsten-containing coating with hardness of 37 GPa, exceeding abrasive hardness of silicon carbide (H about 30 GPa).

The present of cobalt and ultra-hard WB particles in metal base provide the PG-10K-01 coating with minimal wear intensity (the highest wear resistance) also under sliding friction conditions upon steel plate in oxidazing and nonoxidazing atmosphere (see Table 2). It is interesting to note, that in contrast to PGSR-1 coating, for more strength PG-10N-01 and PG-10K-01 coatings

in sliding friction tests the transition from nonoxidazing argon atmosphere to air lead to significant (by exponent) wear intensity growth (see Table 2). The increased frictional wear in the air with relatively low sliding speed of metal material, possessing high enough strength, is caused by embrittlement of ultrafine (nanocrystalline) friction structure during their oxygen enrichment.

Let us consider electromagnetic characteristics of the coatings and the possibilities of eddy-current testing of their composition, hardness, wear resistance and thickness. It is known that eddy current transformer transducers signals are proportional to generalized eddy current parameters β_μ, which is determined by the values of the effective magnetic permeability $\mu_{eff} \sim \mu_{init}$ [12] and the electrical resistivity ρ of the material $\alpha \sim \beta_\mu \sim \sqrt{1/\mu_{eff} \cdot \rho}$ under constant measurement conditions and low exciting field corresponding to Rayleigh region. Measurement, carried out on flat sample with the side of 7×60×2 mm, showed that if for St3 steel μ_{init}=133 and ρ=18.8 μΩ·cm, then during clad coating portion increase in sample to 60-65 % initial magnetic permeability goes down to μ_{init}=22-31 and opposite electrical resistivity go up to ρ=39.5-51.1 μΩ·cm. During further clad coating portion increase in sample to about 95 % the reduction of magnetic permeability to μ_{init}=1.5-4.0 and the growth of electrical resistivity to 122-148 μΩ·cm take place. Therefore observed in Fig 3 decrease of α value during approach to steel ferromagnetic base is caused by sharp growth of initial magnetic permeability, which have significantly larger influence on eddy current characteristics than reduction of electrical resistivity in transition from clad coating to sample steel base. It should be noted that for alloys, based on iron, the change character of readings of eddy current instrument is also defined to a greater degree by change of initial magnetic permeability, than electrical resistivity [13-15].

The presence of substantial difference in eddy current parameters of concidered coatings (see Table. 3), differing by chemical and phase composition, hardness and wear resistance (see Table 1, 2; Fig. 3) is an evidence of possibility of testing by eddy current method of chemical composition, hardness and wear resistance of different types of laser clad coatings. It is important to note, that the educts point at principal possibility of eddy current testing of presence on steel product surface of weak-magnetic wear-resistant Cr-Ni and Cr-Ni-Co coatings, obtained by gas powder laser clad coating method. It was previously reported about using of eddy current method for testing of metal alloys properties with low magnetic permeability [16].

Rated penetration depth of electromagnetic field into clad coatings turned out to be significantly larger, than into ferromagnetic steel base of sample. Particularly rated depth for clad coating was 1.0-2.1 mm for frequency f=72 kHz, 1.8-3.1 mm for frequency f=24 kHz, and for f=2.4 kHz rated depth can reach to 9.7 mm. By comparison one can note that rated depth is only equal to 0.4 mm for St3 steel at frequency of f=2.4 kHz. Therefore, during eddy current testing of clad samples the electromagnetic field attenuation often take place in ferromagnetic steel base.

The observable in Fig. 4 persistent growth of readings of eddy current instrument α with increase of coatings thickness is caused by decrease of initial magnetic permeability of analyzable layer, as ferromagnetic steel sample base influence on measured electromagnetic parameters decreases. The established unambiguous dependence of eddy current control parameter on geometrical dimension of clad layer (see Fig. 4) shows, that eddy current method can be used with great adequacy for thickness evaluation of clad coatings of various composition without application of metallographical control on witness sample. Because after laser clad coating the surface grinding is certainly carried out, the offered technique allows controlling the thickness of finish-ground clad layer. In most cases laser cladding is carried out for the purpose of increase of product wear resistance or reconstruction of surfaces worn-out in service. Therefore it is advisably to use the examined technique not only at a product manufacturing stage, but also while it is in service – for evaluation of residual thickness of coating subjected to severe wear (destruction). It offers the prospects for forecasting using eddy current method of residual life of clad quick-wearing products of mechanical engineering.

Conclusions

The formed by gas powder laser clad coating method Cr-Ni and Cr-Ni-Co coatings, differing by chemical composition of strengthening phases and metal base and possessing by various hardness and wear resistance levels, are characterized by different eddy current characteristics. It points at application possibility of eddy current method for control and evaluation of chemical and phase composition, hardness and wear resistance of laser clad coatings of various type.

For investigated coatings the higher value of readings of eddy current instrument than for steel base are typical because sharp (tensfold) decrease of initial magnetic permeability dominates over increase of material electrical resistivity in transition from high- ferromagnetic base (St3 steel) to weak-magnetic Cr-Ni and Cr-Ni-Co coatings. Therefore, eddy current method allows testing the presence of wear resistance laser clad coating on the steel base.

The application technique of electromagnetic eddy current method for control and thickness evaluation of Cr-Ni and Cr-Ni-Co coatings, formed on steel surface by gas powder laser cladding method. The sensitivity of eddy current method of coatings thickness evaluation grow up during measurement at low frequencies, under which the layer of significant thickness is analyzed, and ferromagnetic base have significant influence on control parameter. The technique allows to estimate the thickness of hardened layer obtained by cladding and subsequent technological operation (for example, grinding). It may be also evaluated the residual coatings thickness which was preserved on surface of product subjected to severe wear in service. This allows to use eddy current method for forecasting of residual life of clad products and monitoring condition of coatings in service, particularly, for definition of critical wear value of coating.

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