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Influence of laser heat treatment on metal coating layers

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The paper presents a research concerning the influence of laser heat treatment on welded coating layers. The research was made with four types of electrodes for welding coating. Evaluation of results was made by researching the microhardness, wear resistance, SEM and EDS. Results reveal a good effect of laser heat treatment in case of coating with electrodes having low carbon and moderate chrome content. Usually, the hardness obtained after coating depends only on the filler material characteristics. The goal of this research is to demonstrate the increasing of hardness after the laser heat treatment of the welded coating layer. The welding coating process enables the recovery by means of reworking of some parts or machine components that reached the wear limit. In this situation, some examples are: dies, crankshafts, different machinery axles, camshaft which can be brought back to the nominal quota. After the analysis of the laser-hardened and remelted shaft under different power conditions, the conclusion was that the laser beam heating produces two kinds of regions inside the laser tracks. One region is composed predominately of martensite; the other region consists of unchanged proeutectoid ferrite, martensite and some pearlite.

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Keywords: Metal coating, Laser beam, Hardness, Microstructure

1. Introduction

Laser surface hardening is a method of producing martensite on selected regions of steel components. A continuous wavelength laser is scanned over the item to heat up the surface to the austenite range (approximately 1000 °C in most steels). Since the substrate acts as an efficient heat sink, the material quickly cools to a temperature below Ms (martensite start temperature). The resulting microstructure is composed of fine martensite, which improves mechanical and chemical surface properties, but maintains unchanged material bulk properties, including ductility and toughness. Because of wide availability, both CO_2 and Nd:YAG lasers have been used to produce hardened surfaces on steels [1].

The current technological problem to be solved is how to propose an alternative route for surface hardening of a specific automotive shaft that has usually been induction-hardened. The laser technology is considered a good candidate because the variety of part shapes to be hardened could pose problems for the induction coil manufacturing and for induction coupling, and also because one wants to choose specific treatment regions. In case of metal coating layers, due to differences between the deposited layer and core, specific problems appear, that have not been adequately studied.

The energy absorbed during laser beam heating is mainly from heat conduction dissipated to the solid volume; thus, the temperature field could be calculated from the heat diffusion equation. Hunziker [2] has proposed a solution for a Gaussian heat source at constant velocity, Vb, over a semi-infinite solid. This solution is based on integration of the uniform source solution originally proposed by Rosenthal [3] with axis origin at the intersection of the laser beam axis with the materials surface. The model assumes constant and isotropic thermal properties, conductivity and specific heat, and negligible latent heat. The steady-state temperature distribution of a Gaussian heat source is then given by:

$$T(x,y,z) = T_0 + \frac{\beta P}{\sqrt{2\pi^3}\kappa} \times \frac{1}{\sigma}\int_0^\infty \frac{\exp(-H)}{1+\xi^2}d\xi$$
$$H = \frac{\left(\frac{x}{\sigma}+\xi^2 P_t\right)+\left(\frac{y}{\sigma}\right)^2}{2\left(1+\xi^2\right)} + \frac{\left(\frac{z}{\sigma}\right)^2}{2\xi^2} \tag{1}$$

where T_0 is the ambient temperature; β is the laser-matter absorptivity; P is the laser power; k is the thermal conductivity; σ is the variance of the Gaussian; ξ is the integration variable calculated as $(\alpha.t)^{1/2}$, with α as the thermal diffusivity and t as the elapsed time; P_t is the Péclet number for thermal diffusion defined as $P_t = \sigma Vb/(2\alpha)$.

High-energy density beam processing is a special technology that uses a high-energy density beam as a heat source for such applications as welding, incision, punching, spray painting, surface treatment, etching, and fine machining [4]. Surface treatments that are effected by laser beam irradiation include laser hardening, laser alloying, and laser cladding [5, 6]. The common feature of all of these processes is the production of certain thermal cycles in small, highly localized regions on the surface of the work-piece, which then takes on new properties that allow it to cope better with wear, fatigue, and corrosion while maintaining most of its other original properties [7].

Recent reviews of the principles and applications of laser treatments describe the use of lasers as a controlled heat source for transformation hardening [8]. The classical approach to modeling the heat flow induced by a distributed heat source moving over the surface of a semi-infinite solid starts with the solution for a point source and integrates it over the area of the beam. This widely used method requires numerical procedures for its evaluation, as do the finite difference solutions of Shuja and co-workers [9]. They developed a 3-D heat flow model and varied the beam power and traverse speed to determine the dimensional analysis of heat flow during heat treating and melting. But the results were not easy discretion of complex shapes and needed complicated calculation. Another approach of heat flow modeling applied to moving heat sources by Rosenthal and several authors have used finite-element method for numerical evaluation, as do the FEM analyses of W. Dai and co-workers [10].

High power diode lasers have reached a high mean power level, a high energy efficiency conversion and a small size of the laser system that permits to mount the whole laser head directly onto the machine, saving a beam guiding system [11]. In short, this kind of laser has become an adequate tool to carry out the ‘‘hardening by transformation’’ [12], especially for the heat treatment of the surface of steel due to the high absorption coefficient for diode laser radiation on shiny or oxidized metal surface. Usually, a cinematic stage to move the sample has to be included in the experimental arrangement to harden a desired surface. Far from the simple experimental set-up, new components for the hardening process have to be employed in order to assure the control of the thickness of the hardened layer without the remelting of the sample surface. The reason to involve more complexity in the experimental system can be attributed to the requirements related to the hardness homogeneity, that can be disturbed not only by the ‘‘noise’’ that affects the processing parameters during the process, but the geometry of the sample to be hardened like complex shaped parts with difficult heat flow conditions (near edges, boreholes or at 3D-curved surfaces) [13]. Furthermore, the reproducibility of the mechanical properties obtained cannot be guaranteed due the in homogeneity of the surface quality that changes the absorption coefficient and as a result the thermal cycles that affect the phase transformation [14].

The welding coating process enables the recovery by means of reworking of some parts or machine components that reached the wear limit. In this situation, some examples are: dies, crankshafts, different machinery axles, camshaft which can be brought back at the nominal quota. Usually, the hardness obtained after coating depends only on the filler material characteristics. The goal of this research is to demonstrate that the increasing of hardness and wear resistance, if a laser heat treatment will be applied on the welded layer.

2. Sample preparation and testing equipment

The metal coating condition was made with arc welding with Luftarc 150 Ductil equipment, using four types of electrodes. The welding current intensity was 700 A and the welding voltage was 40 V. The base metal was S275JR SR EN 10025-2:2004, 20 mm thick. The coating layer was 5 mm thick. After the coating, the samples were tempered at 600ºC. The results were evaluated with PMT – 3 micro-hardness tester, electronically microscope Nova Nano SEM and chemical analyzer EDAX Orbis Micro-XRF.

3. Experimental research

Laser heat treatment was applied on four types of welding coating layers, presented in Table 1. The sample was subjected to laser heat treatment in nine variants, with laser source Nd:YAG – Rofin DY 570 Germany, directed with ABB – Sweden robots.

Table 1. Electrodes used in research.

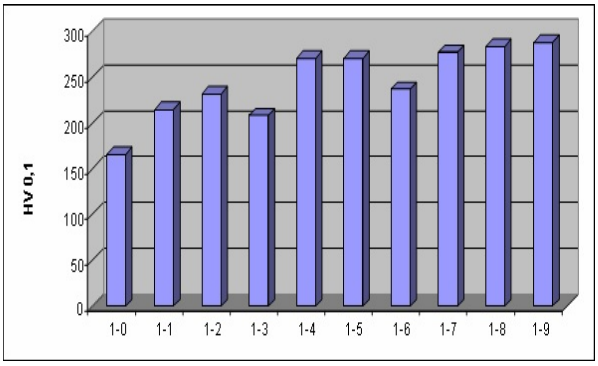
Electrodes	C	Si	Mn	Cr	W	Nb
ElCrW8Co	0.3	0.8	0.8	2.0	7.0	1.2
El CrW2	0.4	1.3	-	1.2	2.3	-
El 62 H	0.7	0.8	0.3	3.5	3	

Table 2. Laser powers and notation of samples

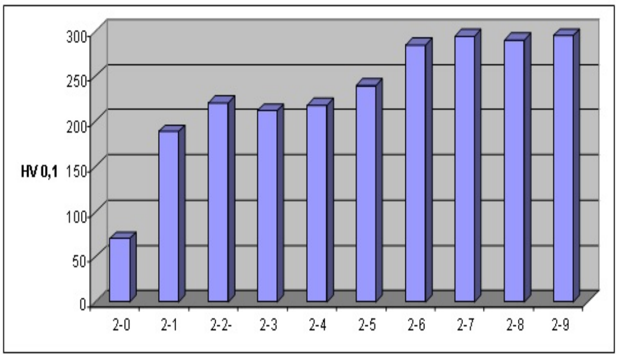
Laser power [W] / Electrode type	Non heat treatment	1400	1500	1600	1700	1875	2150	2425	2600	2700
El CrW2	[1-0]	[1-1]	[1-2]	[1-3]	[1-4]	[1-5]	[1-6]	[1-7]	[1-8]	[1-9]
ElCrW8Co	[2-0]	[2-1]	[2-2]	[2-3]	[2-4]	[2-5]	[2-6]	[2-7]	[2-8]	[2-9]
El 62 H	[K-0]	[K-1]	[K-2]	[K-3]	[K-4]	[K-5]	[K-6]	[K-7]	[K-8]	[K-9]

4. Evaluation of results

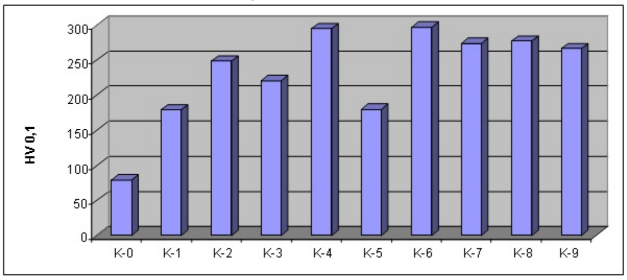
4.1 Micro-hardness



a) Metal coating with electrode El CrW2



b) Metal coating with electrode ElCrW8Co



c) Metal coating with electrode El 62 H

Fig. 1. Variation of micro-hardness.

In the case of coating with El CrW2 electrode (Fig. 1a), which has 0.4% Carbon, and the alloys elements are very low, maximum is Vanadium (3%), the influence of laser heat treatment is very good, the micro-hardness increasing from 151 $HV_{0.1}$, in the case of classical heat treatment after welding coating, to 274 $HV_{0.1}$, 206 $HV_{0.1}$ and 236 $HV_{0.1}$, in the case of application the laser heat treatment after welding coating.

In the case of coating with electrode ElCrW8Co (figure 1b), which has a medium carbon content of 0.45%, and alloys elements are relatively high, Cr – 2%, W - 7%, the effect of laser heat treatment is very good for microstructures and micro hardness. So the micro hardness in case of classical treatment (600ºC) after welding coating the micro hardness is 87,6 $HV_{0.1}$, and in the case of application of laser heat treatment after welding coating the micro hardness is 128 $HV_{0.1}$, 151 $HV_{0.1}$, 160 $HV_{0.1}$.

In case of coating with El 62 H (figure 1c), which have big carbon content 0.7%, the effect of laser heat treatment has significantly increased the micro-hardness starting with 1400 W laser power.

4.2 Wear resistance

Determination of wear resistance was made with determination of weight loss after 15, 30, 60 and 120 minutes of wear the samples were weighed with ”Oertling - England” balance, accuracy 10^{-2} grams. Results are presented in the wear diagrams (figures 2...4).

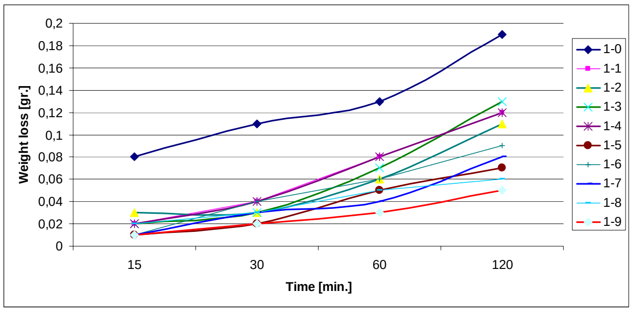


Fig. 2. Wear resistance of metal coating layers with ElCrW2.

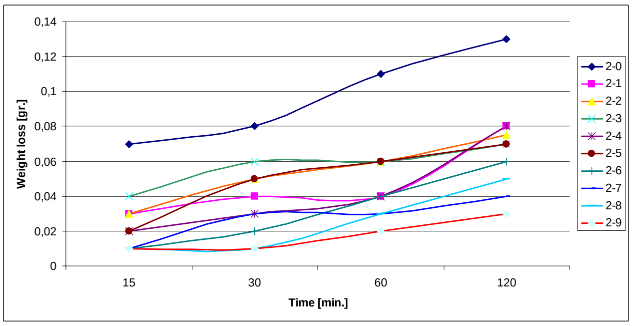


Fig. 3. Wear resistance of metal coating layers with ElCrW8Co.

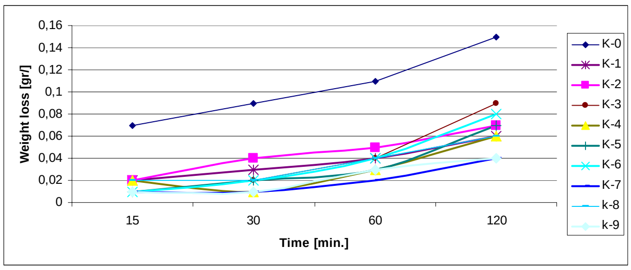


Fig. 4. Wear resistance of metal coating layers with El62H.

In wear diagrams, in Fig. 2 to figure 4, variations of wearing resistance are presented. The tests were made measuring of mass loss after 15 minute, 30 minute, 60 minute and 120 minute. The diagrams present a comparison between the case of just surface coated (non TT) and different variants of laser surface heat treatment after surface coating with different powers. In all cases one can observe the wearing resistance is much better when applied surface hardening with laser after surface coating, rather than tempering at 600ºC.

4.3 Electronically microscopy - SEM

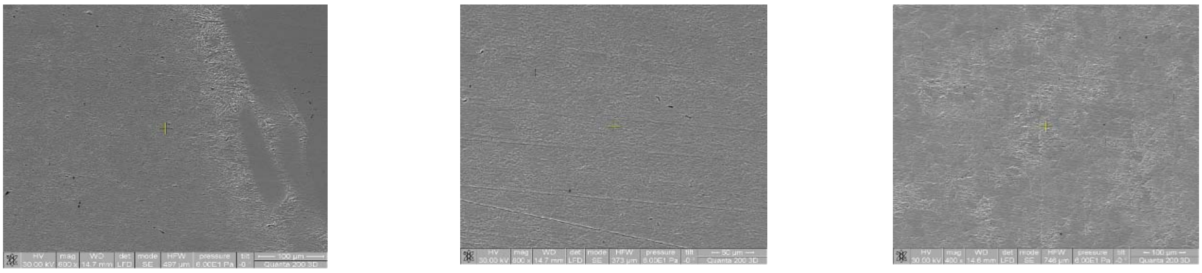


Fig. 5. SEM metal coating layers with ElCrW2+ laser surface hardening 1700 W

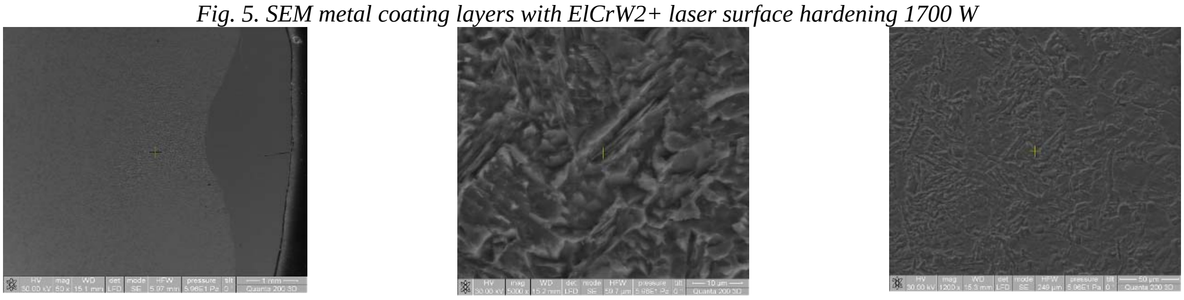


Fig. 6. SEM metal coating layers with ElCrW2+ laser surface hardening 2700 W

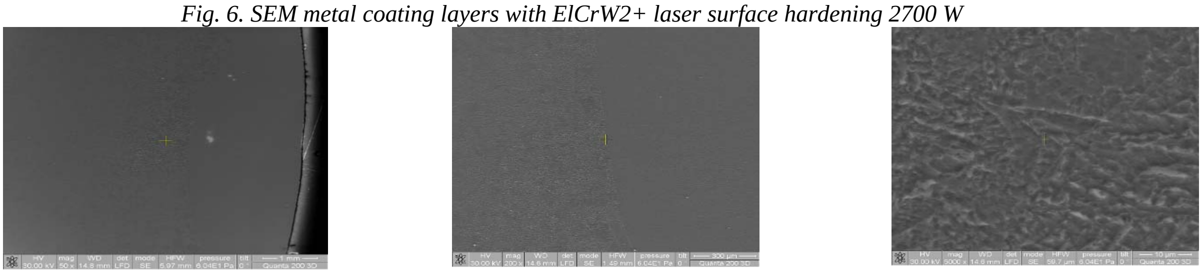


Fig. 7. SEM metal coating layers with ElCrW8Co+ laser surface hardening 2425 W

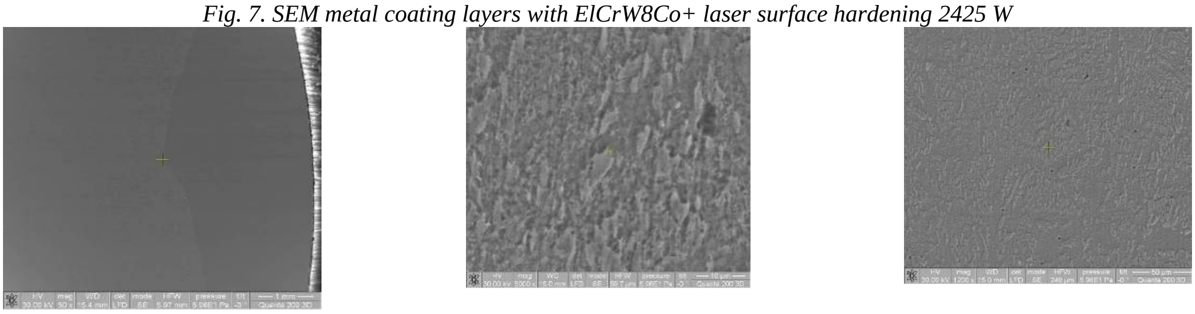


Fig. 8. SEM metal coating layers with El 62 H+ laser surface hardening 1400 W

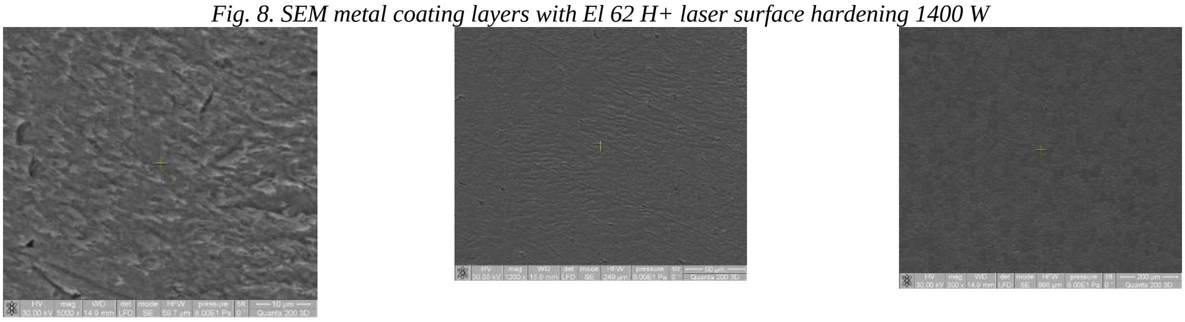


Fig. 9. SEM metal coating layers with El62H+ laser surface hardening 2150 W

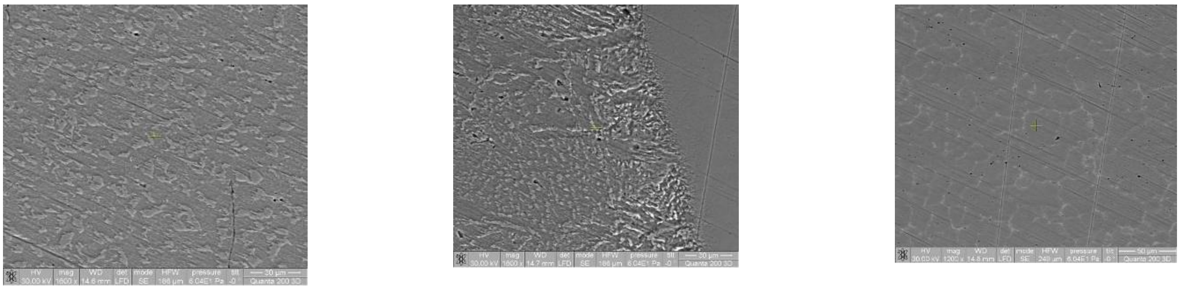


Fig. 10. SEM metal coating layers with El62H+ laser surface hardening 2425 W

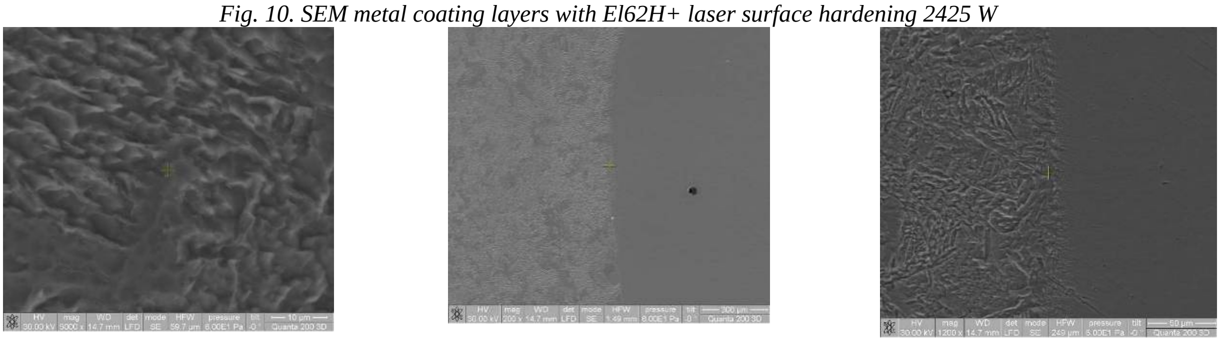


Fig. 11. SEM metal coating layers with El62H+ laser surface hardening 2700 W.

Analyzing the SEM structures one can observe that the interface between these two kinds of martensite is not visible and the martensite itself has similar shape and dimensions at the centre or the surface of the track. The martensite laths have a typical width of 0.2 µm in all analyzed parts of the specimen. From the figure, the melted layer only surpasses 50 µm in depth when the laser power is 1800 W. During heating, the eutectoid structure of pearlite quickly changes to austenite when the temperature rises above A_{c1}. The rapid diffusion of C between cementite and ferrite is aided by the small spacing of these phases, only about 0.3 µm. This means that the interface between the base material and the heat treat zone is quite sharp, as observed, and the reaction does not need overheating. Therefore, the phase transformation from pearlite to austenite begins just above A_{c1}. On the other hand, the reaction between the austenite and the proeutectoid ferrite at A_{c3} requires long-range diffusion of C and other elements, as well as a BCC-to-FCC phase change.

4.4 Chemical Composition – EDS

Studying the EDS chemical analyzing results, one can observe in case of metal coating layers with El CrW2 (fig. 12) after laser surface hardening with 2700 W power, when formation the vitrified structures, the Cr content determinate formation of Cr chemical compound. In case of electrode El CrW8Co (fig. 13) when the Cr content is smaller the percent of Cr chemical compound is small. In case of electrodes El 62H (fig. 14) when the Cr content is bigger because C content is big, the formation of Cr chemical compound is blocked.

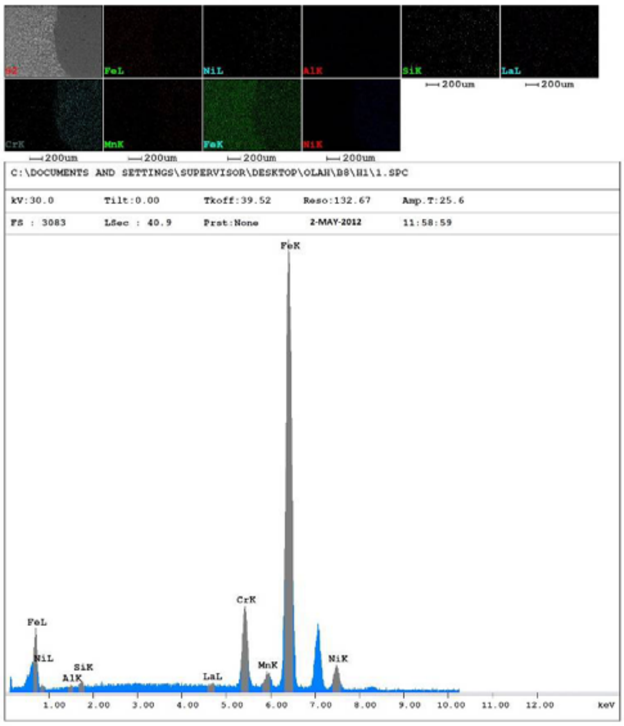


Fig. 12. EDS metal coating layers with ElCrW2+ laser surface hardening 2700 W

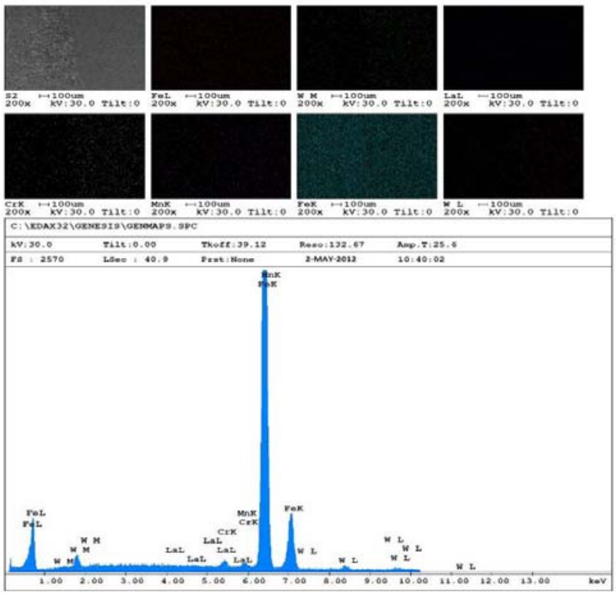


Fig. 13. EDS metal coating layers with ElCrW8Co+ laser surface hardening 2425 W.

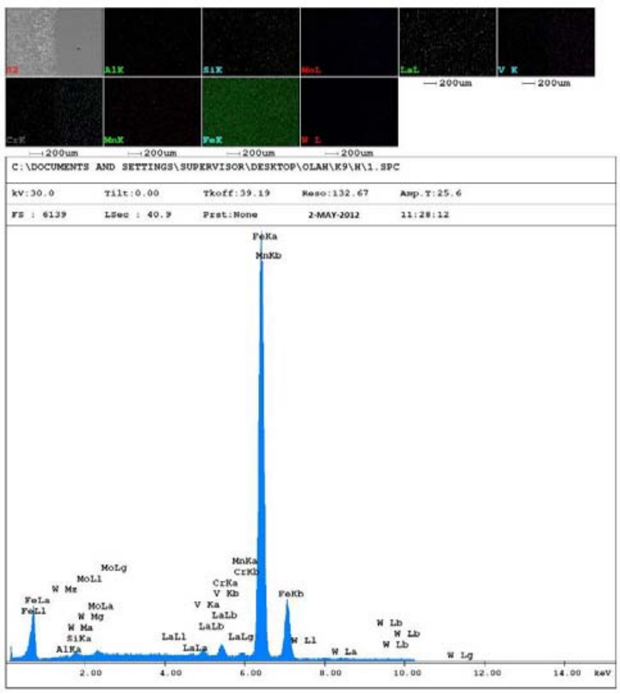


Fig. 14. EDS metal coating layers with El62H+ laser surface hardening 2700 W.

5. Conclusions

In terms of microstructure, the longitudinal cross-section metallography revealed two regions: one composed of martensite, and the other composed of proeutectoid ferrite, unchanged pearlite and martensite. Except at 1400 W where the material remained practically unchanged, the rippled shape of the upper surface indicates that part of the martensite came from melting followed by rapid solidification. Another portion of martensite, after the resolidified layer, came from the homogenization of the microstructure, austenitization and rapid cooling.

The base material has ferrite – pearlite structure, with lamellar pearlite. This research reveals columnar – dendrites structures in Fe matrix with god delimitation. One can observe the metal coating layers is influenced by the laser heat treatment, by disappearing of dendrites structures, appearing the compound of Carbon and Chrome conglobated in the Fe matrix.

Distribution of chemical composition in EDS analyzes reveals the increasing of chemical compound of C and Cr. This increasing follows the increasing of intensity of laser surface treatment. Same influence is observed in dilution of Fe percentage of this element extracting.

After the present analyses of the laser-hardened and remelted shaft under different power conditions, the following conclusions could be drawn:

- The laser beam heating produces two kinds of regions inside the laser tracks. One region is composed predominately by martensite, and other region present is unchanged proeutectoid ferrite, martensite and some pearlite;
- The case depth varies with the laser power. The maximum hardened depth is 0.3 mm for a laser power of 2700 W. Under high power, 1400 and 1800 W, the laser tracks partially overlap; therefore, some tempering occurs at the overlapped zones;
- The current methodology shows a promising alternative to induction-hardened shafts and could be easily implemented within the production process. The method is rapid and allows treatment of specific surfaces on the piece.
- Increasing of C content determines increasing of micro-hardness and wear resistance (fig. 2...4). Increasing of Cr content, determines formation of chemical compound (fig. 12) that also effects increase of wear resistance.
- As one may notice from the experimental outcomes, the samples with laser heat treatment present a wearing resistance that is mostly superior to the classically thermal treated samples. In the case of laser heat treatment layers, the existence in the chemical combination layer of isolated dot-shaped pores does not significantly influence the hardness of the laser heat treatment area or the cohesion with the diffusion sub-layer. It does allow though the enhancement of surface lapping capacity as a result of lubricant retention in the superficial pores, linked to the surface through channels.
- The optimal thickness of the combination layer with best wearing resistance is 10 - 20μm.
- The current methodology shows a promising alternative to induction-hardened metal coating layers and could be easily implemented within the production process. The method is rapid and allows treatment of specific surfaces on the piece.

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