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Laser borided composite layer produced on austenitic 316L steel

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ABSTRACT

Austenitic 316L steel is well-known for its good resistance to corrosion and oxidation. Therefore, this material is often used wherever corrosive media or high temperatures are to be expected. The main drawback of this material is very low hardness and low resistance to mechanical wear. In this study, the laser boriding was used in order to improve the wear behavior of this material. As a consequence, a composite surface layer was produced. The microstructure of laser-borided steel was characterized by only two zones: re-melted zone and base material. In the re-melted zone, a composite microstructure, consisting of hard ceramic phases (borides) and a soft austenitic matrix, was observed. A significant increase in hardness and wear resistance of such a layer was obtained.

1. INTRODUCTION

AISI 316L steel was characterized by an effective balance of chemical composition, i.e. carbon, chromium, nickel and molybdenum concentrations, causing an excellent corrosion resistance. This material was commonly used in aggressive corrosive environments, both at the ambient temperature and at elevated temperature. The relatively low hardness (200 HV) was usually an important disadvantage of this steel. It resulted in its poor wear resistance and was the reason for its limited use. 316L steel could not be subjected to conventional heat treatment because of its austenitic structure. Therefore, there was no easy way to increase wear resistance of this steel [1].

There were attempts to improve tribological properties of the stainless steels using the methods widely applied for constructional or tool steels, such as nitriding, carburizing or boronizing [2-11]. Glow discharge assisted low-temperature nitriding of 316L steel was investigated [2, 3]. This process (at 440°C for 6 h) caused the formation of a thin layer (4 μm) composed of chromium nitrides (CrN) as well as of austenite supersaturated with nitrogen [2]. The increase in process temperature up to 550°C (823 K) resulted in producing the layer of the thickness about 20 μm [3]. Additionally, iron nitrides (Fe_4N) were observed in microstructure at higher temperature [3, 4]. The layers also contained Cr_2N chromium nitrides [5]. Low-temperature plasma carburizing was also applied to improve the properties of stainless steels [6-9]. Such a process, carried out below 520°C (793 K), produced the austenite which was supersaturated with carbon and was characterized by an expanded lattice. Chromium carbides as well as expanded austenite and martensite appeared after carburizing at higher temperature [6]. The thickness of these layers didn't exceed 50 μm. Pack-boronizing was also carried out for austenitic steels [10-12] in the range of temperature 800-950^{o}C, without sacrificing corrosion resistance. The microstructure consisted of two-phase boride layer (FeB + Fe_2B). After the process at a temperature of 950°C for 8 h, the layer obtained a thickness of 90 μm [10].

Laser modification was well-known as an alternative method for improving the tribological properties. In recent years, laser beam was being used for a wide range of applications in order to modify the microstructure and properties of the metals and their alloys [13, 14]. The most important laser processes were as follows: laser-heat treatment, laser alloying and laser overlaying. Laser boriding of steels [15, 16], nodular cast iron [17], titanium and its alloys [18-21] or Ni-based alloys [22, 23] was also intensively

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developed. The hard particles were often introduced to the material surface by the laser treatment. The laser processing might be controlled so as to minimize or promote the dissolution of these particles in the re-melted substrate, leading to a wide variety of metallurgical structures and properties [24]. Laser alloying was applied for 316L stainless steel in order to improve its hardness and wear resistance by incorporating carbides [25] or borides [26].

In this paper, laser boriding of 316L steel was studied as an interesting alternative for diffusion process. The cylindrical surface of the samples was laser-borided with overlapping of 86% like the processes for pure titanium and Inconel 600-alloy previously reported [21-23]. It caused obtaining the uniform laser-borided layer in respect of its thickness, and the laser-borided layer was significantly thicker than that-obtained in case of diffusion boriding. The microstructure, hardness and wear resistance of the produced laser-borided layer were analyzed and discussed.

2. EXPERIMENTAL PROCEDURE

AISI 316L austenitic steel was investigated. Its chemical composition was presented in **Table 1**. The ring-shaped specimens (external diameter ca. 20 mm, internal diameter ca. 12 mm and height ca. 12 mm) were used in the study.

Table 1. Chemical composition of material used [wt pct]

Material	C	Cr	Ni	Mo	Mn	Si	Fe
316L	0.023	17.45	12.92	2.88	0.56	0.45	balance

The two-step laser alloying process was carried out to produce composite surface layer on 316L steel. The paste, consisting of amorphous boron blended with a diluted polyvinyl alcohol solution, was used as an alloying material. First, the external cylindrical surface of the specimen was coated by this paste. The thickness of paste coating (t_C) was equal to 200 or 230 µm. Then, the coated surface was re-melted by the laser beam (**Figure 1**).

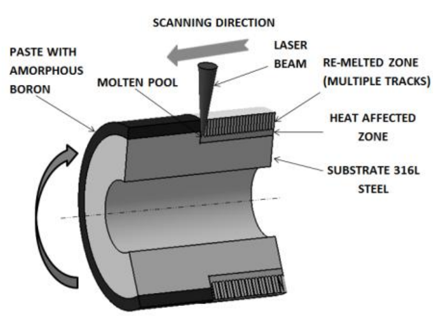

Fig. 1. The two-step method of laser-boriding

Laser heat treatment (LHT) was carried out using the TRUMPF TLF 2600 Turbo CO_2 laser of the nominal power 2.6 kW. Laser processing parameters were as follows: laser beam power P = 1.82 kW and scanning rate v_l = 2.88 m/min. The diameter of the laser beam d was equal to 2 mm. TEM_{01^*} multiple mode of the laser beam was applied. Hence, the averaging irradiance (E) of about 58 kW/cm^2 was obtained. The focusing mirror was characterized by: curvature 250 mm, diameter 48 mm and focal length 125 mm. The laser tracks were arranged as multiple tracks (**Figure 2**), with the distance f = 0.28 mm.

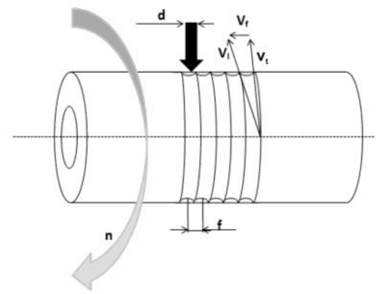

Fig. 2. Method of multiple tracks producing;
d – laser beam diameter (2 mm); v_f - rate of feed; v_l – scanning rate; n - rotational speed; v_t – tangential rate; f – distance from track to track

It corresponded to the distance between the axes of the adjacent tracks and to the feed rate used. The obtained scanning rate v_l (2.88 m/min) resulted from the rotational speed n (45.85 min^{-1}) and feed rate v_f (0.28 mm per revolution). Laser processing was realized in argon shielding at a pressure of 0.2 Pa. The relatively high overlapping of the laser tracks (86%) was applied. This value was calculated using the equation as follows:

$$O = \frac{d - f}{d} \cdot 100\% \qquad (1)$$

where: d is a laser beam diameter [mm], f is the distance between the axes of adjacent tracks [mm], and O is the overlapping.

The microstructure of polished and etched cross-section of the specimen was observed by an optical microscope (OM) and scanning electron microscope (SEM) Tescan Vega 5135. In order to reveal the microstructure, the etching solution, consisting of anhydrous glycerin, HCl and HNO_3, was used with a volume ratio of 2:3:1. Phase composition was analyzed using PANalytical EMPYREAN X-ray diffractometer with Cu K_α radiation. Microhardness profiles, through the investigated layer, were determined in the polished cross-section of specimen. The Vickers method was applied for microhardness measurements using the apparatus ZWICK 3212 B. The tests were performed under the indentation load of 0.1 kgf (about 0.981 N).

Wear resistance test was applied to evaluate the tribological properties of the produced layer and of the material without treatment. The frictional pair consisted of a cylindrical specimen and a plate-shaped counter-specimen, made of sintered carbide S20S. The scheme of wear was shown in **Figure 3**. The sintered carbide was composed of: 58 wt% of WC, 31.5 wt% of (TiC + TaC + NbC), and 10.5 wt% of Co. Such a material obtained a mass density of 10.7 g/cm^3 and hardness of 1430 HV. The wear tests were conducted under conditions of dry friction (unlubricated sliding contact) using the load P = 49 N and the specimen speed of 0.26 m/s, resulting from the rotational speed n=250 min^{-1} and the external diameter of the specimen (20 mm). The laser treatment caused a change in surface roughness of the sample, which was not specially prepared before the wear test. Wear resistance was evaluated by relative mass loss of specimen and counter-specimen ($\Delta m/m_i$) according to the equation:

$$\frac{\Delta m}{m_i} = \frac{m_i - m_f}{m_i} \tag{2}$$

where: Δm is mass loss [mg], m_i is initial mass of specimen or counterspecimen [mg], m_f is final mass of specimen or counterspecimen [mg].

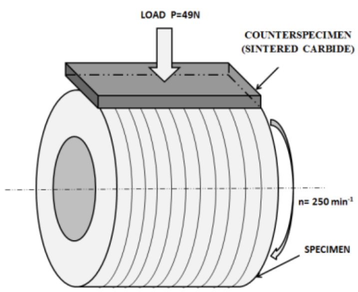

Fig. 3. Scheme of wear test. P = 49 N, rotational speed n=250 min^{-1}

3. RESULTS AND DISCUSSION

3.1. Microstructure

OM microstructures of laser-alloyed 316L steel using boron as alloying material were shown in **Figure 4**.

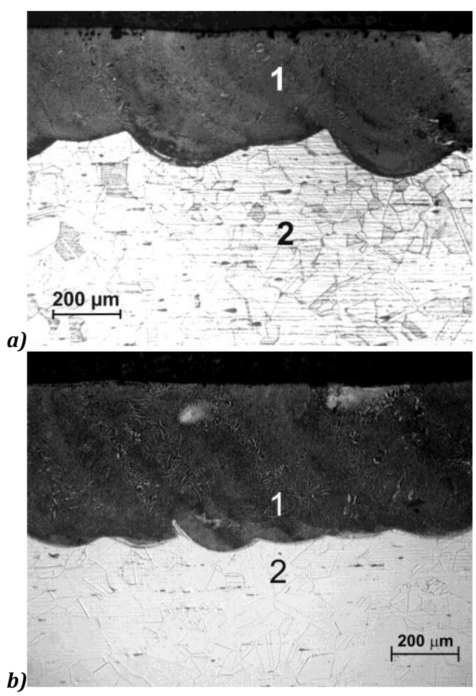

Fig. 4. Microstructure of laser-borided 316L steel at laser beam power of 1.82 kW using paste coating with thickness: 230 μm (a) and 200 μm (b); 1 – remelted zone (MZ); 2 - substrate

The laser treatment was carried out at laser beam power of 1.82 kW using the two thicknesses of paste coating with boron (200 and 230 μm). The continuous laser-borided layer was obtained at the surface. Two zones were visible in the microstructure: MZ - laser re-melted zone (1) and the substrate (2). There were no changes in microstructure below MZ, and heat-affected zone (HAZ) was invisible. The reason for such a situation was that an austenitic structure of 316L steel could not be quenched, irrespective of cooling rate obtained during LHT. The microcracks as well as gas pores were not detected in the laser-alloyed layer. The use of thinner paste coating with boron (200 μm) resulted in higher depth of MZ and more uniform layer in respect of the thickness (**Figure 4b**).

Literature data [10-12] reported the presence of iron borides (FeB and Fe_2B) after diffusion boriding of austenitic steel. After laser boriding, Fe_2B, Cr_2B and Ni_2B borides were identified in MZ based on the obtained XRD patterns (**Figure 5**).

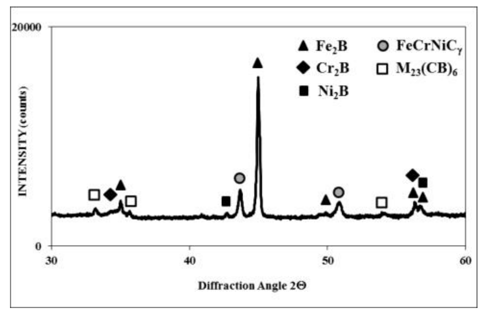

Fig. 5. XRD patterns of laser-borided 316L steel

Additionally, the FeCrNi austenite and borocarbides $M_{23}(C,B)_6$ were observed in this zone. Hence, the laser alloying with boron caused the formation of a composite layer. SE image of MZ indicated the presence of composite microstructure, consisting of hard ceramic phases (iron, chromium and nickel borides) and soft austenitic matrix (**Figure 6**). It was previously observed for laser-fabricated Fe-Ni-Co-Cr-B austenitic alloy on 316L steel [24].

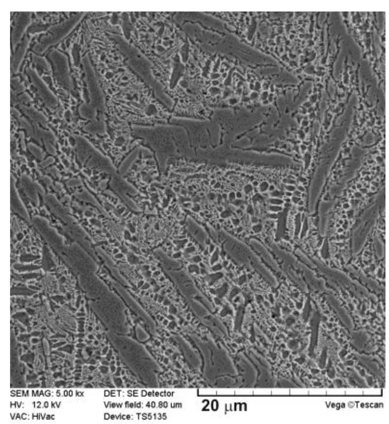

Fig. 6. SE image of re-melted zone (MZ). Hard ceramic phases (iron and chromium borides) in a soft austenitic matrix

3.2. Microhardness profiles

The microhardness profiles of laser-borided layers produced on austenitic 316L steel were shown in **Figure 7**. The measurements were performed perpendicular to the laser-alloyed surface along the axis of laser track as well as along the contact of adjacent tracks. In **Figure 7a**, the microhardness profiles along the axis of track were compared for two used thicknesses of paste coating (200 and 230 µm). The use of thicker paste coating with boron (230 µm) resulted in smaller depth of hardened re-melted zone (MZ). It was accompanied by higher hardness of this zone (up to 740 HV). The higher percentage of hard borides in austenitic matrix was the reason for such a situation. In case of thinner paste coating with boron (200 mm), the maximal hardness of MZ obtained about 600 HV. Hardness of MZ gradually decreased at the end of MZ because of the diminished percentage of borides, obtaining finally the hardness of the base material (160-190 HV). The slightly smaller depth of MZ was also observed at the contact of adjacent tracks (**Figure 7b**). However, the hardness of MZ was very similar, irrespective of the place of measurements (along the axis of laser track or along the contact of tracks).

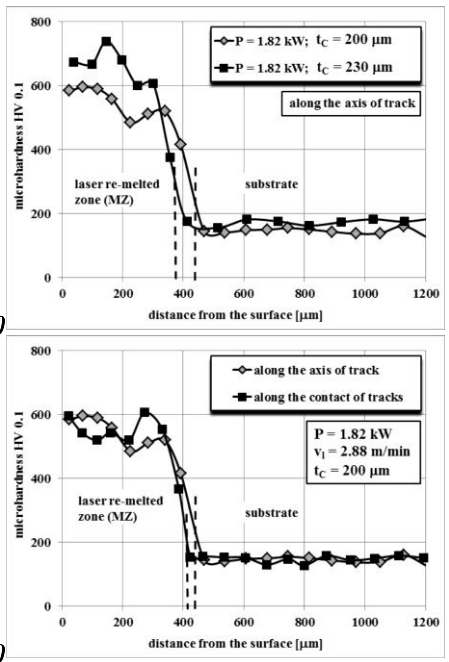

Fig. 7. Microhardness profiles of laser-borided layer formed on 316L steel: along the axis of track at various thickness of paste coating t_C (a), at the thickness of paste coating t_C = 200 µm, depending on the measurement place (b)

3.3. Wear tests

Wear resistance test was performed for laser-alloyed layer obtained with the use of thinner paste coating with boron (200 µm). Specimen was investigated for one hour with a change in the counter-specimen (sintered carbide) every half an hour. The results were compared to those-obtained for 316L steel without treatment [25] and were presented in **Figure 8**.

The evaluation using relative mass loss of specimen and counter-specimen $\Delta m/m_i$ indicated the significant increase in wear resistance of laser-borided layer in comparison with untreated 316L steel. The specimen with the produced layer was characterized by the considerably lower relative mass loss than that-obtained in case of austenitic steel without treatment. The wear of counter-specimen (sintered carbide S20S) was very small in comparison with the examined samples.

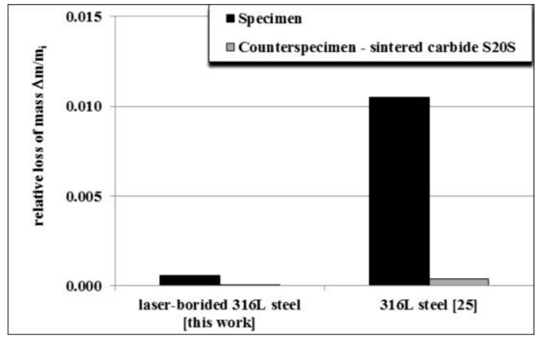

Fig. 8. The results of wear resistance tests

4. CONCLUSIONS

Laser alloying with boron was applied in order to produce composite surface layers on austenitic 316L steel. The microstructure was characterized by only two zones: laser re-melted zone (MZ) and the substrate. There were no visible effects of heat treatment below MZ in microstructure. Heat-affected zone was not observed because austenitic steel could not be hardened by typical heat treatment (austenitizing and quenching). The composite microstructure of MZ consisted of hard ceramic phases (iron, chromium and nickel borides) with a soft austenitic matrix. The uniform laser-alloyed layers in respect of the thickness were produced because of the relatively high overlapping of multiple laser tracks (86%). Cracks and gas pores were not observed.

The significant increase in hardness was characteristic of produced surface layers. Hardness of MZ obtained 600 HV and 740 HV, depending on the thickness of paste coating with boron. At the end of MZ, hardness gradually decreased to the values characteristic of the substrate (160-190 HV) because of the increased percentage of soft austenitic matrix. The use of thinner paste coating with boron resulted in higher depth of re-melted zone. It was accompanied by diminished hardness because of the lower percentage of hard borides in austenitic matrix.

Laser alloying with boron caused also a significant increase in wear resistance. Relative mass loss of laser-borided specimen was approximately ten times lower than that-measured for austenitic 316L steel without treatment.

The applications of proposed layers in industry will require the appropriate corrosion resistance. It should be examined in the future and should be compared to the properties of 316L steel without surface layer.

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