LASER CLADDING OF INCONEL 686 OVERLAY WELD ON LOW CARBON STEEL

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Abstract

The work presents the effects of the change of the laser cladding parameters on microstructure, chemical composition and mechanical properties of Inconel 686 overlays (coatings). To obtain the best quality of these coatings the various parameters of laser cladding such as the power density of the laser beam, the laser beam velocity and overlapping ratio of the weld tracks were applied. The substrates were boilers plate made of the 13CrMo4-5 steel. Ni - base alloys characterize by the excellent high-temperature corrosion resistance, good strength and good ability to work in aggressive environments. This could be achieved by the reduction of the substrate melting and its dissolution into the overlays. The microstructure, chemical composition of the obtained overlays were investigated by means of a light microscope, a scanning electron microscope (SEM) equipped with the EDS detector. The overlays had cellular-dendritic structure. The variations of the chemical composition (especially Mo, Ni and W) in the interdendritic and dendritic regions were observed. The interdendritic regions were enriched during solidifications in Mo and W and had lower content of Ni.

Keywords: Laser cladding, overlay, chemical composition, Inconel 686

INTRODUCTION

Laser-cladding is one of the most relevant new processes in the industry due to the particular properties of the produced parts. It is used in many branches of the industry, including aerospace, automobile, shipbuilding, oil and gas, transport, power engineering, etc. During laser cladding, the surface of the substrate is melted by laser irradiation and a melt pool is created. The powder is either injected into the melt pool with a nozzle using an inert carrier gas. A powder stream is formed once the powder particles exit the nozzle tip. The powder becomes molten and is captured by the melt pool, afterwhich it mixes with the substrate material. Metallurgical bonding takes place between the coating material and substrate by the solidification of the melt pool. Shielding gas (such as argon, nitrogen, helium and mix of them) is used to protect the melt pool against oxidation. A clad track is produced on the substrate surface when the laser beam and powder stream are travelling together with respect to the substrate [1]. The main advantage of laser-cladding process is the possibility of obtaining high quality material deposition on complex parts [2]. However, one of the main technical problems is to prevent the occurrence of micropores and cracks, although it has been demonstrated that this technology has the potential to form pore-free and crack-free coatings [3]. In fact, micropores and microcracks are frequently observed in the deposited layers [4 - 6]. Especially in aggressive environments, one of the major problems in the deposited coatings is the presence of open pores, closed pores and microcracks in the overlays which can substantially reduce the overlay's mechanical and protective properties, such as the resistance of corrosion, microhardness and bonding strength [7]. The cladding quality is generally characterized by the profile of the clad coatings, thickness of the heat affected zone, thermal stresses, porosity, microcracks, etc. [8 - 9]. Process parameters, e.g., the power laser denisity of the laser beam, powder feed rate, nozzle scanning velocity and the spot diameter deemed the main factors that influence the cladding quality. Laser welding can be suggested as a coating technology for nickel alloys used to cover walls of power boilers and pipe superheaters in order to protect against high-temperature corrosion. Nickel superalloys are widely used in the power industry because of its high corrosion resistance. During the cladding process it is important to provide the lowest amount of the energy (heat) to the substrate in order to minimize the quantity of the iron into the overlay. Too high amount of Fe (above 10 % for automatic cladding process) in the coatings leads to decrease resistance to high-temperature corrosion. Using laser beam technology it is possible to closely control the process parameters such as beam energy density, laser beam velocity, beam spot size, powder feed speed, etc. Properly selecting above mentioned parameters it is achievable to obtain overlay with specific properties and without welding defects.

1. MATERIALS AND EXPERIMENTAL METHODS

In this study, the Q-Switch Nd:YAG JK System 5000 laser beam was used with an off - axial powder feeding laser cladding system, which indicates that the Nd:YAG laser beam with the wavelength of the laser radiation λ = 1064 nm, metal powder and shielding gas (argon) were injected simultaneously from the two nozzles during the process. The metal powder Ni-Cr-Mo-W (Inconel 686) was deposited on cleared and degreased surfaces of the samples of 13CrMo4-5 steel (ISO EN 10028 - 2 - 2003). Their chemical compositions are listed in **Table 1**. Before laser cladding process the substrate surface (13CrMo4-5 steel) was polished using 600 gradation sandpaper and clean by alcohol C_2H_5OH. To study the influence of the power density of the laser beam (q), in the investigation was conducted under various q = 4.4 - 7.8 kW, whilst the cladding velocity (4-5 $mm{\cdot}s^{-1}$), different overlapping ratio of next clad tracks (20 - 50 %), the powder feed rate (8 $g{\cdot}min^{-1}$) and the laser spot diameter (500 µm) were constant for all specimens - A, B and C (**Table 2**).

The substrate material is widely used in the power industry owing to its good properties of strength and plasticity, as well as good welding property compare to volume of price/ tone. The Inconel 686 metal powder used in the investigation is a kind of Ni-Cr-Mo-W alloy with the particle size between 70 - 100 µm (**Figure 1**). This powder is characterized by its high temperature properties, showing high strength, hardness, excellent corrosion and wear resistance at elevated and high temperatures. Detailed parameters of the cladding process are listed in **Table 2**. To obtain the proper thickness of the overlays (about 2 - 2.5 mm) which is require for overlap weld layers in power plant industry, four layers (one on another) were set. To determine the microstructure and the changes of elements distribution in the overlays, the light microscopy, the scanning electron microscopy (SEM) and energy dispersive spectroscopy (EDS) were applied. The examination of the overlays microstructure and chemical composition were performed with the FEI Inspect S50 and FEI Nova NanoSEM 450 scanning electron microscopies. Microhardness of overlays was measured on transversal microsections along paths perpendicular to the surface with a Vickers microhardness tester (Wolpert-Wilson TUKON 2500) with the load of 9.8 N applied for 10 s.

Table 1 Chemical composition of the base material - steel Cr13Mo4-5 and the Inconel 686 powder

Cr13Mo4-5 steel - Base material (BM)									
C	Si	Mn	P	S	Cr	Mo	N	Cu	Fe
0.08 - 0.18	0.35	0.4 - 1	0.025	0.01	0.7 - 1.15	0.4 - 0.6	0.012	0.3	Balance
Inconel 686 - Powder									
Cr	Mo	Fe	W	Mn	P	S	Ti	C	Ni
19 - 23	15 - 17	<5	3 - 4.4	<0.75	<0.04	<0.02	0.02 - 0.25	0.01	Balance

Table 2 Laser cladding parameters of three samples

Sample/ Parameters	Power density ($kW{\cdot}cm^{-2}$)	Laser beam velocity - - V, ($mm{\cdot}s^{-1}$)	Powder feed rate, ($g{\cdot}min^{-1}$)	Overlapping ratio of next clad, (%)
A	4.4	4	8	50
B	7.8	5	8	20
C	6.6	5	8	30

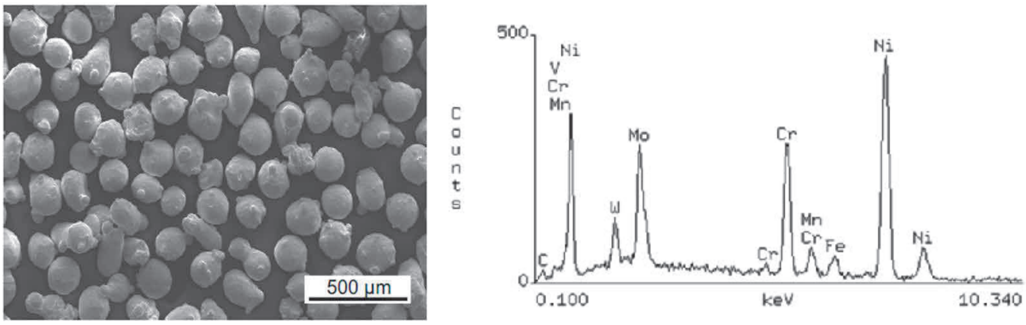

Figure 1 SEM image of the Inconel 686 powder and its EDS X - ray analysis

Table 2 Quantitative EDS X - ray analysis of the Inconel 686 powder

Element	Weight %
W - M_α	2.5
Mo - L_α	12.0
Cr- K_α	18.8
Mn - K_α	1.9
Fe - K_α	3.5
Ni - K_α	61.1

2. RESULTS AND DISCUSSION

2.1. Optical Microscope investigation

The overlays were subjected to observation by light microscope. Observations showed that in each sample a correct metallurgical connection of overlay to the substrate was obtained. **Figure 2** presents the obtained overlays as a result of the various cladding parameters applying. Two zones were formed as a result of laser cladding of surface layers of the 13CrMo4-5 steel with the Ni-based alloy, namely: the Inconel 686 overlay and a heat-affected zone (HAZ) (**Figure 2**).

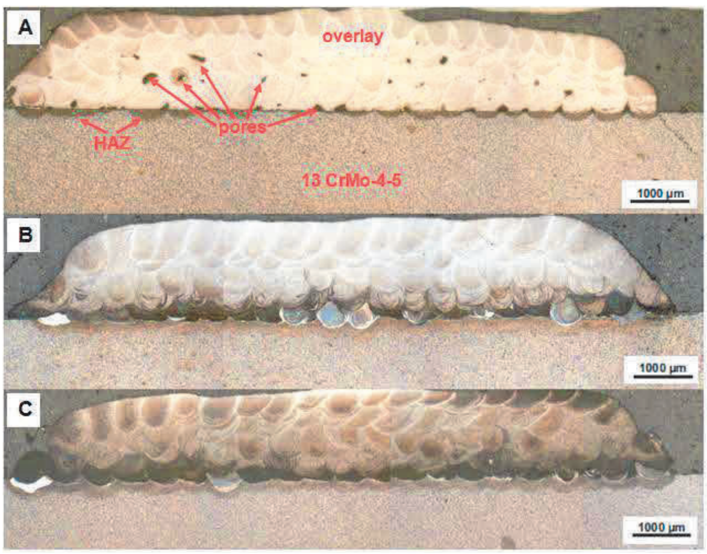

Figure 2 Microstructure (LM) of the Inconel 686 overlay. a) sample A (q = 4.4 kW; V = 4 mm·s^{-1});
b) sample B (q = 7.8 kW; V = 5 mm·s^{-1}); c) sample C (q = 6.6 kW; V = 5 mm·s^{-1}), HAZ - heat affected zone

The application of the lowest power density led to the formation of porosity between the weld tracks, inside the overlays and in the boundary of the base material and the heat affected zone (HAZ) (**Figure 2A**). On the other hands too low a laser beam energy density could lead to insufficient melting of the powder and a substrate. However, the increase of the beam energy density enabled the welds to be free of welding defects (**Figures 2B, C**). As the consequence of very fast cooling rate from the solidifying laser melt pool a very thin heat-affected zone (approximately 200 μm thick) was created. The thickness of the coatings to be applied was about 2 mm.

2.2. Microstructure and chemical composition of the Inconel 686 overlay

Scanning electron microscope observations have identified the typical nickel alloy overlay weld cellular - dendritic structure with increased content of alloy elements in interdendritic regions (**Figures 3, 4**). High cooling and solidification rate are typical for laser processing and in the consequence the "freezing" of the structure and the microsegregations form. Liquid metal in the laser pool flows outwards from the centre of the weld pool along the upper surface to the outside edge and returns below the surface. Therefore the movement of the liquid material (melted pool) resulted in characteristic "swings" (**Figure 3**). In these areas the chemical composition of the particular elements (Ni, Mo, W, and Fe) changed. **Figure 3** presents SEM image of coating structure after laser cladding and EDS chemical composition of dendritic and interdendritic regions. In the interdendritic regions could notice a higher concentration of molybdenum and tungsten than in the dendrites cores.

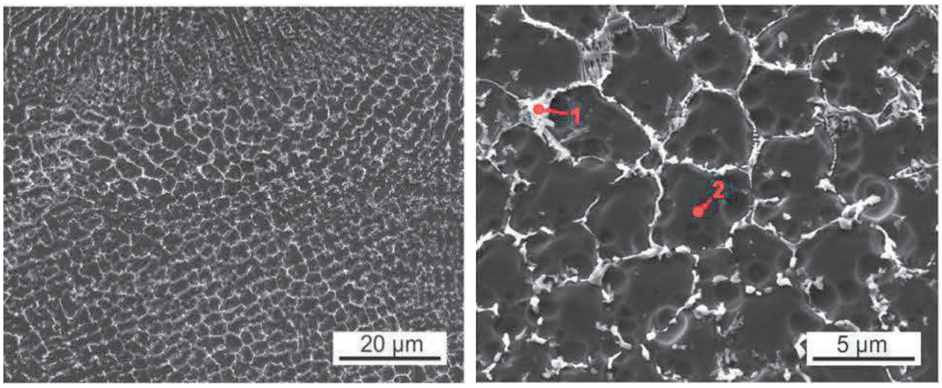

Figure 3 SEM micrograph showing the Inconel 686 coating and the marked area of the point EDS X - ray analysis, 1 - the interdendritic regions, 2 - the dendrite core

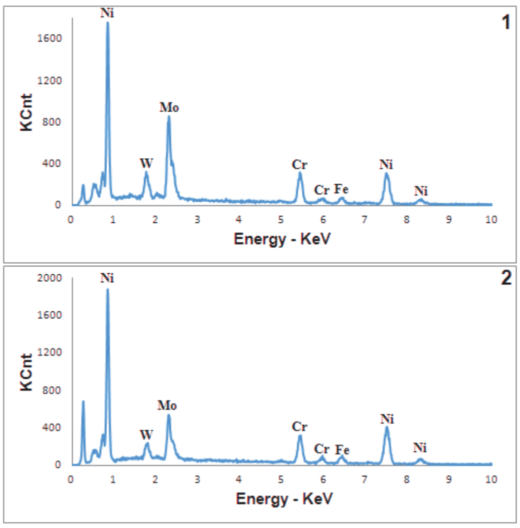

Figure 4 The EDS point analysis of the dendritic and interdendritic regions in the overlay

Table 4 Quantitative chemical analysis of the Inconel 686 overlay

Element/ characteristic X-ray line analyzed	Point - 1	Point - 2
	Weight %	
Cr-Kα	14.4	14.9
Fe-Kα	4.3	5.8
Mo-Lα	26.3	15.7
Ni-Kα	41.5	53.9
W-Mα	13.5	9.7

In case of coatings which are used to protect steel against corrosion in aggressive environments very important is amount of Fe which is implement to the coatings during cladding process. Depending on the amount of supplied laser beam energy required to obtain proper metallurgical bonding between the overlay and the substrate modify the chemical composition of the overlay. The higher power density can lead to increased iron content. To high amount of iron in the surface layer has high influence on corrosion process and can accelerate degradation of coatings. The line EDS analysis showed that in two samples (A, B) amount of Fe was about 20 % which is overmuch (**Figure 5**). In third sample (C) amount of Fe in the coating surface was 10 %, which is acceptable, however the application of the lower power beam and higher laser beam velocity during cladding process should obtain lower amount of iron in overlay.

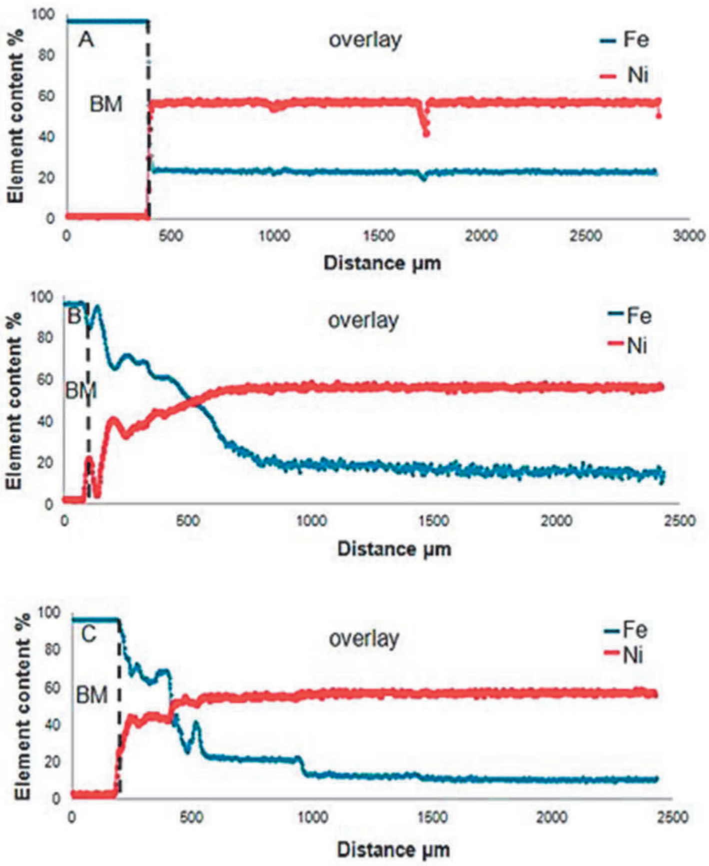

Figure 5 Distribution of nickel and iron in the Inconel 686 overlays: a) sample A (q = 4.4 kW; V = 4 $mm \cdot s^{-1}$); b) sample B (q = 7.8 kW; V = 5 $mm \cdot s^{-1}$); c) sample C (q = 6.6 kW; V = 5 $mm \cdot s^{-1}$)

2.3. Microhardness of the Inconel 686 overlays

The microhardness of the substrate reached about 170 HV1. The highest value of hardness, of about 350 HV1, was obtained at the overlays, which can be explained by the presence of a fine-crystalline structure and the presence of the martensite and higher concentration of Cr and W. The microhardness of the heat-affected zone reached about 375 HV1 and it decreased due to the absence of chromium and tungsten in its structure.

CONCLUSIONS

Two zones were generated in the processed laser cladding of surface layers of 13CrMo4-5 steel: the Inconel 686 overlay and a heat-affected zone. The cladding of nickel alloy allowed to create a good metallurgical bonding with the base material. Each bonding was characterized by a narrow heat-affected zone (200 µm) and complete melting of the nickel alloy powder. Structural examinations of the overlays showed the presence of considerable grain size reduction and occurrence of the cellular-dendritic structure. In the interdendritic regions the content of molybdenum and tungsten increased while the nickel content decreased in comparison with the dendrite cores. The results of the study have confirmed that the main parameter of the cladding process is the power density of the laser beam. The supplied amount of the energy during melting of Inconel 686 powder and the substrate has significant impact on the cooling rate of the melt pool, which has a principal role in shaping the macrostructure of the overlay. Too low energy density results in the formation of the multiple pores, however too much laser energy accelerates the entering of iron towards to the surface of the overlay, which can cause the reduce of the high corrosion resistance of the weld overlays.

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REFERENCES

[1] WEI Y., PATHIRAJ B., SHAOJIE L. 2D modeling of clad geometry and resulting thermal cycles during laser cladding*. Journal of Materials Processing Technology,* 2016, no. 230, pp. 217-232.

[2] ABBAS, G., WEST D., Laser surface cladding of stellite and stellite - SiC composite deposits for enhanced hardness and wear. *Wear* 1991, no. 143, pp. 353-363.

[3] ASSUNCAO E., WILLIAMS S., YAPP D. Interaction time and beam diameter effectson the conduction mode limit. *Opt. Lasers Eng.* 2012, no. 50, pp. 823-828

[4] BRÜCKNER F., LEPSKI D., BEYER E. Modeling the influence of process parameters and additional heat sources on residual stresses in laser cladding. *J. Therm. SprayTechnol*. 2007, vol. 16, pp. 355-373.

[5] CHO, C., ZHAO, G., KWAK, S.Y., KIM, C.B. Computational mechanics of laser cladding process. *J. Mater. Process. Technol.* 2004, no. 153, pp. 494-500.

[6] KUSINSKI J., WOLDAN A., KAC S. Modification of the steel surface layer for its better wear resistance by means of laser melting and alloying. *Proceedings of SPIE (The International Society for Optical Engineering*), 2003, vol.5229, pp. 155-162

[7] CHAO Z., WEI T., WEN H. L., LIANG H. Microstructure and porosity evaluation in laser- cladding deposited Ni-based coatings*. Surface and Coatings Technology,* 2016, no. 294, pp. 122-130.

[8] PAREKH R., KUMAR BUDDU R., PATEL R. I. Multiphysics simulation of laser cladding process to study the effect of process parameters on clad geometry*. Procedia Technology,* 2016, vol. 23, pp. 529-53.

[9] RADZISZEWSKA, A., KRANZMAN, A., DOERFEL, I., et al. Microstructure and chemical composition of Fe - Cr alloy tempered in high temperature and Atmosphere containing Ar - SO_2. *Archives of Metallurgy and Materials*, 2016, vol. 63, pp. 1261-1265