Dependence of the structure and characteristics of a Russian alternative for AISI 304 stainless steel powder on the parameters of their laser cladding on substrates from low-carbon and structural steels

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Abstract. The work studies X8 CrNiSiMg 17-8-6 steel powder, a Russian alternative for AISI 304 steel, cladded by ytterbium fiber laser on two types of substrates: heat-resistant steel and low-carbon steel. The results demonstrate the effect of laser radiation power on the macrostructure of single cladded beads and their fusion with the substrate. The selected regimes allow forming solid cladded layers. The paper also studies the microstructure of metallographic sections of cladded specimens, the phase composition of cladded layers and initial powder. The deliverables include the data on wear resistance, resistance to intercrystalline corrosion and strength of cladded layer fusion with the substrate.

1. Problem Formulation
Implementation of fiber lasers for cladding layers of stainless and heat-resistant steels enables production of more wear resistant, higher-quality and denser coatings compared to conventional cladding methods. This method heats the part less and provides stronger fusion with the substrate [1]. High cooling rate of the cladded layers induces a characteristic microstructure that appreciably affects final mechanical and chemical properties of the coatings [2, 3]. Inaccurate selection of cladding regimes inevitably leads to defects in the layers, either inside them or inside the fusion with the substrate. Such strongly negative effects can be avoided in two ways: a) modeling or selection of optimal heat input and focal distance of the laser; b) implementation of a special multi-channel nozzle forming the flux of sputtered powder as a purely technological solution to make the cladded layers more sinterable. The work is to study the properties of Russian X8 CrNiSiMg 17-8-6 powder sputtered in an inert gas (argon) through the multi-channel nozzle directed by ytterbium fiber laser on a steel substrate under varied power and laser velocity, to discover and control the properties of such coating.

2. Laser cladding technology
The stainless-steel powder was cladded on two types of low-carbon steel: X12 CrNiTi 18-10 austenitic heat-resistant alloyed steel and X9 MgSi 2 structural ferrite low-alloyed steel. The cladding powder was represented by X8 CrNiSiMg 17-8-6 steel, a Russian alternative for AISI 304 stainless steel.
Laser cladding was performed by LRC laser robotic complex composed of LS-5 ytterbium fiber laser, Fanuc six-axis robot with coaxial powder feeding nozzle, two-axis positioning device and AT-1200 powder feeder.

2.1 Selecting optimal laser-cladding regime
This work considered ten regimes of laser cladding sorted according to laser radiation power. The main parameters of laser cladding (radiation power, produced layer hardness, substrate melting and maximum depth of heat-affected zone) are presented in Table 1. The laser velocity was selected according to the substrate heat capacity.

| No. | Power (W) | Hardness      | Substrate melting | Heat affected area (mm) |
|-----|-----------|---------------|-------------------|------------------------|
| 1   | 600       | 90-140 HB     | no                | 0.6                    |
| 3   | 800       | 150           | no                | 0.6                    |
| 4   | 1000      | 150–160 HB    | yes               | 0.8                    |
| 5   | 1250      | 120-150 HB    | no                | 1                      |
| 6   | 1500      | 150-170 HB    | yes               | 1                      |
| 7   | 1600      | 150-250 HB    | yes               | 1.3                    |
| 8   | 1700      | 150-270 HB    | yes               | 1.3                    |
| 9   | 1800      | 100-150 HB    | yes               | 1                      |
| 10  | 1900      | 150 HB        | yes               | 1                      |
| 11  | 2000      | 150–200HB     | yes               | 1.3                    |

Table 1. Main cladding parameters

The specimens were cross-cut to produce metallographic polished samples that were studied by optical microscopy (Figures 1 and 2). Obviously, there are separate beads represented by a surface with two components: main body (Figure 1-I) and metal outflow from the main pool (Figure 1-II) formed after powder melting under the action of the shielding gas jet providing total crossing of the beads during formation of solid cladded layer.

3. Structure and mechanical properties of cladded layers
After trying several regimes of laser cladding, three regimes of laser beam energy input were selected. Figures 3–5 demonstrate edge polished samples of beads cladded in three regimes, correspondingly. Their main parameters are presented in Table 2.
Table 2. Main parameters

| No.  | Energy per unit length (W/m) | Hardness | Substrate melting | Heat affected area (mm) |
|------|-----------------------------|----------|-------------------|------------------------|
| Regime 1 | 240< ~ 30 HRC           | yes     | ~ 2.5             |
| Regime 2 | >500 ~ 30 HRC           | yes     | ~ 2.5             |
| Regime 3 | 240<x>500 ~ 30 HRC     | yes     | ~ 1.5             |

Figure 3. End polished sample cladded in regime 1

Figure 4. End polished sample cladded in regime 2

Figure 5. End polished sample cladded in regime 3

The metallographic slices demonstrate solid cladded layers: in regime 1, the substrate is not fully penetrated during formation of first beads (Figure 5-I) and on consequent incomplete mixing of cladded metal and base substrate metal (Figure 5-II); in regime 2, there is excessive penetration with incomplete mixing of the substrate metal. Regime 3 demonstrates the most optimal formation of cladded layers with partial penetration of the substrate, minimum formation of separate micropores and absence of substantial negative effects, including cracks and lacks of penetration.

4. Tribological properties

The cladded layers were used to produce samples for studying their tribological properties on a versatile friction machine. A hardened spherical tip made of high-carbon alloyed steel was used to make spherical friction tracks under load and without lubrication on the surface of the cladded layers to reveal the behavior of the friction coefficient during wear and to establish qualitative dependence of the wear resistance as the specimen mass loss on the path, load and velocity (Tables 3 and 4).
Table 3. Measurement parameters

| Substrate                          | Velocity (m/s) | Load (N) | Distance (m) | Mass loss (g) |
|------------------------------------|----------------|----------|--------------|---------------|
| 09G2S (European A 516-55 steel)   | 0.2            | 10       | 1000         | 0.042         |

Tribological test results of stainless steel laser cladding on the 09G2S substrate are presented as plots in Figures 6 and 7.

Figure 6. Dependence of friction coefficient on distance and load

Figure 7. Dependence of friction coefficient on distance and load

Tribological test parameters for stainless steel laser cladding on X12 CrNiTi 18-10 substrate are presented in Table 2. The results are presented in Figures 8 and 9.

Table 4. Measurement parameters

| Substrate                  | Velocity (m/s) | Load (N) | Distance (m) | Mass loss (g) |
|----------------------------|----------------|----------|--------------|---------------|
| X12 CrNiTi 18-10           | 0.2            | 10       | 1000         | 0.05          |

Figure 8. Dependence of friction coefficient on distance and load

Figure 9. Dependence of friction coefficient on distance and load

The results of tribological tests have demonstrated similar mass loss for both substrate types (Tables 3 and 4). The cladded material wear on the stainless steel substrate (Figures 7 and 8) is characterized by a longer uniform section, unlike the layers applied on low-carbon steel where the plot is nonuniform starting from the beginning of the experiment, which is probably conditioned by different structure of cladded layers, depending on heat sink through the substrate material.
5. Phase analysis

X-ray diffraction (XRD) analysis was performed on a D8 ADVANCE X-ray diffractometer. The structure of the iron component of initial powder is represented by austenite and ferrite with prevailing ferrite component (Figures 10 and 11) [4]. Cladding on austenitic steel surface allows obtaining primarily austenitic structure (up to 95% of austenite, Figures 12 and 13), unlike cladded layers of ferrite steel surface, which structure remains austenitic-ferritic with prevailing fraction of austenite up to 79.21% (Figures 14 and 15).

Figure 10. Dependence of intensity on 2θ angle

| Show | Icon | Color | Index | Name | Parent | Scan | Pattern | Compound Name |
|------|------|-------|-------|------|--------|------|---------|----------|
| Yes  | 🌈   | 🌈    | 1     | COO 015927 | COD 015927 | C-parasite | H-parasite #1 | COD 015927 |
| Yes  | 🌈   | 🌈    | 12    | COO 013418 | COD 013418 | C-parasite | H-parasite #1 | COD 013418 |

| Formula | Y-Type | Inc DB | Inc User | S-Q | Added Reference | d by | Scan WL | Wavelength |
|---------|--------|--------|----------|-----|-----------------|------|---------|------------|
| Fe      | 82.45% | 0.70   | 48.88%   | 1.000 | Yes             | 1.000 | 1.50000 | 1.500000   |
| Fe      | 98.172%| 13.260 | 63.6%    | 1.000 | Yes             | 1.000 | 1.50000 | 1.500000   |

| System  | Space Group | a      | b      | c      | alpha | beta | gamma | Z | Volume | Density | Cell Toned | F [W] |
|---------|--------------|--------|--------|--------|-------|------|-------|---|--------|---------|------------|-------|
| Calce   | m-3 m (223)  | 3.56500| 3.56500| 3.56500| 45.45| 45.45| 45.45| 1 | 12.879 | 1.00000 | 1.000000 | 1.00000 |
| Calce   | m-3 m (223)  | 2.85300| 2.85300| 2.85300| 90.00| 90.00| 90.00| 1 | 23.27  | 1.00000 | 1.000000 | 1.00000 |

Figure 11. Results of phase composition investigation of initial powder

Figure 12. Dependence of intensity on 2θ angle
6. Microstructure analysis

The microstructure of cladded layers was studied in the optical range using a metallographic microscope. The heat affected zone of the substrate metals primarily demonstrates medium-grain structure, which is connected with the grain growth under the thermal effect conditioned by heat sink through the substrate in the presence of small-grain component (Figure 16a). The cladding structure, a separate bead in particular (Figure 16b), demonstrates appreciably ramified dendrite structure formed along the heat sink lines during crystallization. The microstructure of the cladded layer is predominantly a solid solution of alloying elements in iron of austenitic type with presence of intermetallides on grain boundaries (Figure 16c).
Figure 16. Metallographic images of cladding

7. Conclusions
High cooling rates during laser cladding of stainless steels have a considerable impact on the microstructure and phase composition; hence, affect their functional properties [5]. With high energy additivity, the formation of layers from powder materials by high-power fiber laser beam is complicated by a considerable problem of balance of velocity and energy density of the laser providing sufficient sintering of cladded layers with minimum formation of pores and burn-off of alloying elements. In the work, the laser beam power was selected to avoid cracking in pre-heated substrate. Cladding was carried out by a four-channel power feeding unit that was forming the deposited layer with set continuity and selected optimal laser input power. As a result, the replacement of a conventional single-axis coaxial nozzle with a four-channel nozzle for cladding by ytterbium fiber laser using LRC-5 at VLSU provides predominant formation from mainly ferrite powders of cladded austenitic layers with dendrite structure and minimum number of separate micropores with a surface hardness of 25–30 HRC without unacceptable defects, including cracks. This will allow using the method for cladding working surfaces suffering simultaneously loads and corrosion, for instance, pipeline valves.

References
[1] Alam M Edrisy A Urbanic J and Pineault J 2017 Microhardness and Stress Analysis of Laser-Cladded AISI 420 Martensitic Stainless Steel Journal of Materials Engineering and Performance 26 3 1084
[2] David S A 1987 Effect of rapid solidification on stainless steel weld metal microstructures and its implications on the Schaeffler diagram Oak Ridge National Lab (USA) 10487
[3] Kurz W Trivedi R 1994 Rapid solidification processing and microstructure formation Materials Science and Engineering 179 46–51
[4] Blawert C Weisheit A Mordike BL Knoop RM 1996 Surf Coat Technol 85 15
[5] Hemmati I Ocel’k V Hosson J 2011 Microstructural characterization of AISI 431 martensitic stainless steel laser-deposited coatings J Mater Sci 46 3405–3414