**Effect of laser cladding parameters on structure properties of cobalt-based coatings**

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**Abstract.** The article presents results of microstructure, microhardness and geometry tests of cobalt-based alloys deposited on low-alloy steel by a laser cladding process. As a deposited material MetcoClad 6 powder was used. Powder is characterized by a spherical shape of particles obtained in inert gas-atomization process with a size of -106 +45 μm suited to a variety of hardfacing processes. The experiments were carried out using a disk laser Yb:YAG TruDisk 3302, with a wavelength of 1.03um equipped with a disc powder feeder. The laser cladding process was carried out at various parameters of cladding speed, beam power and powder feed rate in order to obtain layers with low dilution, low porosity and good coating uniformity. Macroscopic studies were performed using a metallographic microscope light stereoscopic Olympus SZX9. Vickers microhardness tests were provided on the cross-section of layers on Wilson Wolpert 401 MVD device.

1. **Introduction**  
Cobalt alloys are widely used in industry as materials applied to the surface layers of machines parts exposed to high mechanical and thermal loads. These materials can be applied for the components that require high resistance to complex atmospheres, high temperatures and abrasive and mechanical wear. The structure of Stellite consists of cobalt and alloying elements such as chromium, tungsten, molybdenum and a small amount of carbon. Chromium is the main element responsible for the formation of interdendritic carbides. The carbides are also formed as a result of the reaction of carbon with elements such as tungsten or molybdenum. The distribution, shape and size of the carbides are mainly determined by the parameters of the process and affects the mechanical properties and hardness of the obtained layer. Cobalt alloys are used in several industries: automotive (surface of valve seats of internal combustion engines), energy (surfaces of valves and valves, erosion shields of steam turbines), metallurgy (rolls), paper industry (chain guides), gas industry (drill bearings). Such a wide application of cobalt alloys results from the high resistance to erosive and sliding wear, cavitation erosion, high-temperature corrosion resistance, and high impact resistance.

Laser cladding is one of the most modern and constantly developed methods for producing coatings. With the use of this technique, it is possible to obtain coatings with properties that are significantly different from the base material. Laser cladding enables extending the service life of machine parts and implementation to work in harsh environmental conditions. This technology enables the production of layers with a thickness of up to 50-100 μm, characterized by a small dilution of 5-10%. The expected coating properties can be obtained already in the first layer. The
limited impact of the laser beam on the workpiece has a positive effect on obtaining small stresses and deformations, enabling the creation of a fine-grained structure with high metallurgical purity [1-7].

The aim of the presented research was to determine the optimal parameters for the laser cladding process of cobalt alloy to achieve high-quality coatings. The research included laser cladding tests, macrostructure and microstructure observations, calculations of solidification time of the coatings and microhardness tests.

2. Materials and methodology

The tested coatings were produced on a 10 mm thick S235JR non-alloy steel substrate, using MetcoClad 6 powder (table 1). The powder was produced by inert gas atomization and the particle size was in the range 45 - 106 μm. The surface of the samples was subjected to grinding and degreasing with acetone before cladding. The samples were placed on a work table, which allows linear motion in the X-axis and Y-axis, while the movement along the Z-axis to adjust the beam focus was carried out by the head feed. For laser cladding process TRUMF disk laser Yb: YAG TruDisk 3302 (table 2) was used. The laser emits a continuous beam with a wavelength of 1.03 μm at a maximum power of 3.3 kW. The laser beam was transmitted from the source to the head using optical fibre. The detailed parameters used for the laser cladding process are presented in table 3. The station was equipped with a disk feeding system for cladding area, with the possibility of precise control of the powder feeding rate in the range from 0.6 to 12 g/min.

Table 1. MetcoClad 6 powder chemical composition.

| Chemical composition (wt.%) | Co  | Cr  | W   | Si  | C   | Ni  |
|-----------------------------|-----|-----|-----|-----|-----|-----|
| Chemical composition (wt.%) | 64.37 | 27.3 | 4.4 | 1.6 | <1.1 | 0.8 |
| Mo  | Fe  | Mn  | P   | S   | Al  |
| 0.1 | 0.1 | <0.1 | 0.01 | <0.01 | <0.01 |

Table 2. TRUMPF TruDisk 3302 laser parameters.

| Characteristic                  | Value |
|---------------------------------|-------|
| Wave length [μm]                | 1.03  |
| Maximum output power [W]        | 3300  |
| Laser beam divergence [mm·rad]  | <8.0  |
| Fibre core diameter [μm]        | 200   |
| Collimator focal length [mm]    | 200   |
| Focusing lens focal length [mm] | 200   |
| Beam spot diameter [μm]         | 200   |
| Fiber length [m]                | 20    |

To develop optimal technological conditions for conducting the laser powder cladding process, preliminary tests were carried out. The study included changes in the parameters: shielding gas flow, powder feed rate and variable focal length to obtain the minimum depth of melting the substrate surface. In the next stage of work, the analysis of the effect of beam power, powder feed rate and cladding speed on the quality of obtained coatings was carried out. Quality was evaluated using the visual testing method. It was observed that the optimal properties of the laser beam for laser cladding process occur when the beam is defocused by raising the head by 20 mm relative to the focus on the treated surface. For the research, 50 mm long single beads were made with constant control of the interpass temperature, which did not exceed 30 °C. To protect the liquid metal and the powder against
oxidation, a 10 l/min argon blow was used through a cylindrical nozzle aligned with powder feed nozzle.

Table 3. Technological conditions of the laser cladding process.

| Shielding gas flow rate – argon [l/min] | Powder transporting gas flow rate – argon [l/min] | An inclination angle of the nozzle relative to the laser head [°] | Powder feeding nozzle diameter [mm] |
|----------------------------------------|-----------------------------------------------|--------------------------------------------------|----------------------------------|
| 10                                     | 3                                             | 30                                               | 2                                |
| Coating number                         | Power [W]                                      | Cladding speed [m/min]                           | Powder feed rate [g/min]        |
| 1                                      | 1250                                          | 0.1                                              | 4.0                              |
| 2                                      | 1250                                          | 0.075                                            | 3.0                              |
| 3                                      | 1875                                          | 0.15                                             | 6.0                              |
| 4                                      | 2500                                          | 0.2                                              | 8.0                              |

For the structural investigation, metallographic specimens were prepared. The samples were cut out in the middle of beads length, where the process parameters have stabilized. For macroscopic observations specimen were etched with 4% Nital, while for microscopic observations aqua regia was used. For the macroscopic observations of coatings stereoscopic microscope, Olympus SZX9 was used. To assess the mixing degree of base material with the coating (Up), the measurements of the coating surface (Fn) and the penetration surface (Fw) were made. The mixing degree was measured by the following formula:

$$U_p = \frac{F_w}{(F_n + F_p)} \times 100\% $$  \hspace{1cm} (1)

The microstructural observations were made using the Nikon Eclipse MA100 light microscope. Based on the analysis of solidification conditions of cobalt matrix alloys carried out by A. Frenk at. al. [7], the clad solidification rates were calculated for each parameters presented in table 3. The authors based on the tests of conventional clad crystallization process and the distance between secondary arm dendrites, determined the possibility of predicting solidification time, according to the formula:

$$T = \left( \frac{32.8}{10^6 \times \alpha_2} \right)^{\frac{3}{2}} $$  \hspace{1cm} (2)

where:

- $T$ – solidification time [K/s]
- $\alpha_2$ – the distance between secondary arm dendrites [m]

Calculations of the distance between secondary arm dendrites were made in the middle part of the cross-section of the coating at 10 different measuring points. The average value was calculated based on the obtained data. In the next stage, calculations were made following formula (2), obtaining data on the solidification time of each coating.

To assess the impact of laser cladding parameters on properties, the Vickers microhardness measurements were made on Wilson Wolpert 401 MVD tester with 200 g load and indenter operation time of 10 s. The measurements were made on the coatings cross-section along one measuring line from the face to the substrate. The distance between the individual measuring points was 0.1 mm.
3. Results and discussion
The macrostructures of obtained during laser cladding process coatings are presented in figure 1. The coatings geometrical parameters (height and width) and mixing degree results are presented in table 4. The analysis of the coatings macrostructures allowed to determine the effect of power and speed parameters correlation on geometrical characteristics of the beads. The coatings no 1-3 (according to table 3) had low mixing degree with the base material. No imperfections in a form of cracks and porosity were identified. Despite the use of the same heat input, samples no. 1, 3 and 4 (according to table 3) showed significant changes in the melting degree of the substrate material. The main factor affecting the observed phenomenon is convection. The intensity of convection increases with the increase of temperature gradient, which is depends on the laser beam power. The increase of laser beam power between sample no. 1 and 2 (according to table 3), influenced the change in the depth of substrate melted zone and the coating shape. The coating produced with higher laser beam power is characterized by a much flatter face and higher mixing degree with the base material. With the increase of cladding speed, while maintaining a constant heat input, an increase of mixing degree was observed. However, no significant changes in coatings cross-section were observed, which indicates a constant and stable value of the melted powder amount.

* Coating number according to table 3

Figure 1. Macrostructures of the coatings produced by laser surface cladding with MetcoClad 6.
The microstructures of produced coatings are presented in figure 2. The microstructural tests allowed to determine the occurrence of three different areas of the coatings: transition, dilution and fine-grained cobalt matrix coating zone. The coatings microstructure is characterized by a typical dendritic structure. At the fusion line, large primary dendrites located perpendicular to the cladding direction can be observed. This is a result of the heat conduction direction, which in the lower part of coatings is directed towards the base material. In the coatings upper part, a change in the direction of dendrite growth and a significant grain refinement can be observed. Multidirectional crystal growth was found in the fine-grained areas of the upper coating zone.

### Table 4. Geometrical parameters and mixing degree of coatings.

| Coating number (according to table 3) | Coating height [mm] | Coating width [mm] | Mixing degree [%] |
|--------------------------------------|---------------------|--------------------|-------------------|
| 1                                    | 1.12                | 4.59               | 6.46              |
| 2                                    | 0.80                | 4.67               | 18.00             |
| 3                                    | 1.04                | 5.00               | 23.00             |
| 4                                    | 1.00                | 5.34               | 36.00             |

The results of solidification time calculations according to formula (2) are presented in table 5. The results show slight changes in the solidification time of the coatings despite the use of different parameters of the cladding speed and the laser beam power, in the range of the same heat input, generating a difference in the range of 120 °C (samples 1, 3 and 4 according to table 3). The change of cladding speed parameter by 0.25 m/min significant changes were observed in the material structure. The microstructure of coating no. 1 was characterized by a much smaller size of dendrites and a fine-grained structure compared to coating no. 2. Such a change of structure significantly affects the abrasion resistance properties of a coating [8].

### Table 5. Solidification time of coatings.

| Coating number (according to table 3) | The average distance between the secondary arm dendrites \(a_2\) [μm] | Solidification time [K/s] |
|--------------------------------------|---------------------------------------------------------------|--------------------------|
| 1                                    | 3.73                                                          | 679.97                   |
| 2                                    | 5.15                                                          | 258.34                   |
| 3                                    | 4.96                                                          | 289.19                   |
| 4                                    | 5.92                                                          | 170.04                   |

The results of Vickers microhardness measurements are presented in table 6 and figure 3. The analysis of the microhardness tests of the coatings shows that with increasing speed and power of the laser cladding process, the hardness measured on the cross-section decreases significantly. The factor affecting this result is the coarseness of the obtained structures, which was confirmed by microscopic observations.
Figure 2. Microstructures of the coatings produced by laser surface cladding with MetcoClad 6, coating number according to table 3: (a) 1; (b) 2; (c) 3; (d) 4.
### Table 6. Vickers microhardness of coatings results.

| Measuring point number | Coating number (according to tab. 3) | HV0.2 value |
|------------------------|---------------------------------------|-------------|
| 1                      | 1                                    | 424 (c) 411(c) 443 (c) 431 (c) |
|                        | 2                                    | 416 (c) 416 (c) 438 (c) 392 (c) |
|                        | 3                                    | 420 (c) 428 (c) 410 (c) 386 (c) |
|                        | 4                                    | 421 (c) 470 (c) 420 (c) 360 (c) |
|                        | 5                                    | 461 (c) 405 (c) 421 (c) 320 (c) |
|                        | 6                                    | 436 (c) 420 (c) 423 (c) 330 (c) |
|                        | 7                                    | 425 (c) 422 (c) 396 (c) 342 (c) |
|                        | 8                                    | 422 (c) 420 (c) 380 (c) 322 (c) |
|                        | 9                                    | 419 (c) 435 (c) 382 (c) 302 (c) |
|                        | 10                                   | 401 (c) 410 (c) 374 (c) 315 (c) |
|                        | 11                                   | 383 (fl) 370 (c) 375 (c) 316 (c) |
|                        | 12                                   | 321 (fl) 322 (fl) 372 (c) 324 (c) |
|                        | 13                                   | 289 (fl) 284 (fl) 316 (c) 310 (c) |
|                        | 14                                   | 279 (fl) 272 (fl) 349 (fl) 296 (fl) |
|                        | 15                                   | 247 (bm) 279 (fl) 336 (fl) 291 (fl) |
|                        | 16                                   | 242(bm) 250 (bm) 312 (fl) 252 (fl) |
|                        | 17                                   | 241 (bm) 240 (bm) 286 (fl) 248 (bm) |
|                        | 18                                   | - - 224 (bm) 250 (bm) |
|                        | 19                                   | - - 230 (bm) - |

Where: c- coating, fl- fusion line, bm- base material

![Figure 3. Coatings Vickers microhardness graph.](image)

### 4. Conclusions
The laser cladding process with cobalt matrix powder MetcoClad 6 on a 10 mm thick S235JR non-alloy steel substrate gives the possibility of producing high-quality coatings without imperfections. The ability to precisely control the process enabled to obtain coatings characterized by a small dilution which was confirmed by microscopic examination. The coatings hardness measured on the cross-
section maintained stable values at the level of approximately 412 HV0.2 confirming that the crystallization conditions were similar in different zones of the coating. This made it possible to obtain homogeneous structures in the cross-section of the coating. It was found that the use of higher laser cladding speed at constant heat input leads to an increase of melting the base material and to reduction in hardness which is caused by a much larger size of the obtained structures.

5. References
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