The formation of heterogeneous wear-resistant coatings by the additive technology method

A A Golyshev, A G Malikov and A M Orishich
Khristianovich Institute of Theoretical and Applied Mechanics SB RAS,
4/1 Institutskaya st., Novosibirsk, 630090, Russia
alexgol@itam.nsc.ru

Abstract. The microstructure, hardness property and wear resistance coatings of WC, Ni-Cr and Fe powders deposited by laser cladding at varying processing parameters were investigated. The results of the present study revealed the prospects of multilayer cladding of R6M5 high-speed tool steel (analogy of M2 steel) onto low-alloy steel with the use of a laser beam. Controlling thermal cycles of laser cladding, it is possible to obtain a clad coating made of high-speed steel having the structure of high-alloy austenite martensite mixture with disperse inclusions of carbides up to 10 mm thick, i.e., it is actually possible to create bimetal structures. The wear resistance of the laser-clad self-fluxing PG-10N-01 (Ni-Cr-B-Si-C) alloy increases by a factor of 5 due to additional hardening by cast tungsten carbide with spherical particles. As a result, it becomes higher than the wear resistance of high-speed steel by more than a factor of 3.

1. Introduction
Laser cladding of powders has been intensely studied recently all over the world as a method of hardening, improving the wear resistance of the material surface, creating high-strength cutting tools, recovery of worn workpieces, etc. To increase the wear resistance of clad layers, metal-composite powders based on Ni-Cr and Co-Cr mixed with carbides and borides are used [1-3].

It was demonstrated [4-6] that the characteristics of abrasion of Ni-based coatings with WC inclusions depend on the volume fraction and distribution of WC particles in resultant coatings. The basic studies are aimed at decreasing cracking in clad layers [7-11]. Researchers also study the microstructure of clad layers, stability of the process, and microhardness [12-15]. However, there are few reported investigations of mechanical properties of workpieces, their strength, abrasion and impact resistance, etc., i.e., actually the operation performance of technological products in absolute values.

In this work, we study the process of laser cladding of R6M5 high-speed tool steel powder (analog of M2 steel (USA) and HS6-5-2 (EU)), which possesses high hardness, a self-fluxing PG-10N-01 (Ni-Cr-B-Si-C) powder and a mixture of a self-fluxing Ni-Cr-B-Si-C powder with tungsten carbide (WC). Absolute values of the wear resistance of resultant clad layers are analyzed and compared. We studied laser cladding of powder mixture Ni-Cr-B-Si-C+ WC with a ceramic WC concentration of up to 45%. As a result received high-quality ceramic-metal coatings (without cracks and pores), measured the wear and microhardness of the coatings.
2. Experimental methods
Controlling the parameters of a highly focused laser beam during the laser cladding procedure allows one to vary the power density and the heating spot size within wide limits. In the present studies, the automated laser technological complex (ALTC) developed and fabricated at the Khristianovich Institute of Theoretical and Applied Mechanics of the Siberian Branch of the Russian Academy of Sciences (ITAM SB RAS) on the basis of a powerful CO₂ laser with convective cooling of test gases [16, 17] was used as process equipment. The microstructure of clad layers was studied by using an Olympus LEXT OLS3000 confocal scanning laser microscope.

3. Laser cladding of high-speed steel
A technological possibility of creating a bimetal material with a matrix made of low-alloy steel and with working surfaces made of R6M5 high-speed steel powder with particles in diameter up to 150-170 µm (its chemical composition is presented in Table 1) by means of laser cladding was studied.

In the present work, the alloying agent was the powder of R6M5 steel, which was distributed prior to laser treatment by a special dispenser-crystallizer onto the base material surface without any binder. The base material had the form of metal sheets shaped as disks 2 mm thick, which were fabricated by means of laser cutting from 65G steel (its chemical composition is presented in Table 1) after complete quenching and tempering to the hardness of 45 HRC.

| Table 1. Chemical composition (percentage). |
|---------------------------------------------|
| Material | C  | Si   | Mn  | Cr  | W   | V   | Mo  | Fe  | Ni  | B   |
| R6M5     | 0.84 | 0.48 | 0.5 | 3.9 | 6.1 | 1.9 | 4.9 | Base| -   | -   |
| 65G      | 0.62-0.7 | 0.17-0.37 | 0.9-1.2 | 0.25 | -   | -   | Base| -   | -   |
| PG-10N-01| 0.4  | 2.6  | -   | 13.5 | -   | -   | -   | Base| 2.0 |

Laser cladding was performed in the optimal mode: laser power of 1.0 kW. The laser beam speed was 1 m/min. The laser radiation is focused on the surface -2 mm.

Interaction of the base and clad metals mainly occurs along the boundaries of austenite grains. After cooling, the melted grains start to act as centers of growth of dendrite crystals of the clad material (figure 1). As the thickness of the powder layer subjected to laser treatment increases, the depth of melt penetration into the base material decreases. If the treated layer thickness is greater than 2 mm, there appear regions where no fusion with the base material occurs; such regions are separated from the base material by an oxide film.

![Figure 1. Metallographic analysis of single-layer cladding with R6M5 steel.](image1.jpg)

![Figure 2. Infiltration of the clad R6M5 layer into the 65G base material.](image2.jpg)

The base material in the laser influence zone (LIZ) becomes structurally inhomogeneous (figure 2) as a result of incomplete quenching of 65G steel, which has a row-by-row distribution of carbides in this case. R6M5 steel used for cladding has a dendrite structure (figure 1). Cross sections of branches...
of high-alloy austenite dendrites accommodate martensite crystals. Carbides Fe3C; Fe2C; Fe3C4, FeC evolve in the space between these dendrites in the form of eutectic colonies and chains of individual particles, which form a continuous skeleton in some places. The microhardness of the austenite-martensite mixture is 9.48 – 10.1 GPa in the zone of cladding material fusion with the base material and 10.1 – 10.9 GPa in the middle part and on the surface.

The thickness of the resultant coating is determined by the purpose and type of cladding. If a thick coating is needed, cladding of several layers can be performed. The thickness of the second and next layers in the experiment was chosen to be approximately 80% of the depth of melting of R6M5 steel. The lower layers are located in the LIZ in the case of layer-by-layer cladding. The chosen regime of repeated laser treatment of the previously clad layer of R6M5 steel ensures favorable changes in the distribution of carbides.

Laser cladding in several passes leads to melting of the network of carbides Fe3C; Fe2C; Fe3C4, FeC separating into individual particles (figure 3 a); carbides dissolve. This, in turn, increases the level of alloying of austenite formed during subsequent crystallization.

![Image](a)

![Image](b)

Figure 3. Structure of the carbide phase of the R6M5 steel coating in the case of laser cladding in several passes (a – middle part of the coating, b – fusion zone).

The structure of the R6M5 steel coating in the front of laser beam motion and after repeated laser cladding is illustrated in figure 4. In the first case (in the front of the melted zone), a high level of etchability, microvoids, and non-metallic inclusions are observed. After re-cladding, carbide eutectic becomes separated into individual particles. The total amount of the carbide phase decreases. The level of alloying of the solid solution simultaneously increases.

The measured microhardness of the structural components of the LIZ is shown in figure 5. The microhardness of the base material with the initial structure of tempered troostite is 5 GPa. During laser treatment, those regions of the base material that are heated to temperatures below the austenization point experience tempering, and their hardness decreases to 3.5 GPa. At the LIZ edges, the austenite phase is mainly formed around carbides. These austenite regions with inhomogeneous concentrations turn during subsequent cooling into an austenite-martensite mixture with microhardness values ranging from 6 to 9 GPa (light areas in figure 2). On the boundary with the clad material, the LIZ temperature ensures homogenization of austenite and its subsequent quenching to martensite with a microhardness value of 11 GPa.
Repeated quenching occurs in the base metal. The martensite hardness is 8.74 GPa. Diffusion processes in the fusion zone begin to develop (figure 3 b). There are only minor changes in the hardness of dendrite cells varying from 9.4 to 10.1 GPa.

Using layer-by-layer cladding, we managed to obtain a coating up to 8-10 mm thick with-out any macroscopic defects and with a hardness value of 63 - 64 HRC. After standard three-fold tempering at 560 °C, the hardness of the clad coating of R6M5 steel increased to 66 - 67 HRC.

4. Laser cladding of the Ni-Cr-B-Si-C alloy powder
We studied cladding of a PG-10N-01 nickel-chrome powder (its chemical composition is presented in table 1) for obtaining a wear-resistant coating, which was performed in optimal regimes at the laser power of 1.65 kW. The laser beam scanned the surface with a frequency of 62 Hz, the beam velocity was 3.2 m/s, and the scanning range was 5 mm. The workpiece feed velocity was 1.2 m/min.

After thermal treatment, the powder alloy becomes completely melted and ensures good fusion with the base material, thus, forming a coating. The resultant coating has a dendrite-cellular structure (figure 6). The finely differentiated eutectic component is identified over the dendrite cell boundaries. No aggregates of primary carboborides are visible. The solid solution has parameters that testify to an increase in the concentration of dissolved components. This fact is indirectly evidenced in this work by the increase in the solid solution microhardness by 10 – 12 % as compared to the microhardness value obtained during volumetric thermal treatment.
Tests with cladding of the self-fluxing nickel-chrome alloy did not reveal any embrittlement effect of the network of carboborides on the dendrite cell boundaries. It was found that an increase in the fraction of solid phases in the clad coating decreases the abrasion and impact wear resistance.

Structural studies show that this is caused by spalling of coating fragments along the brittle carbide network on the dendrite cell boundaries. However, in view of the high hardness of the coating, it can be expected to exhibit a high wear resistance value during its operation in a volume filled by abrasive particles and in the case of its dragging on a fixed abrasive material.

5. Laser cladding of the Ni-Cr-B-Si-C alloy (PG-10N-01) and WC.
Based on the data obtained, compositions of cladding materials of the self-fluxing nickel-chrome alloy (PG-10N-01) and WC were composed, with the ratio 55:45%. These compositions were fed in the form of a fine-grain powder and spheroidized particles of cast tungsten carbide.

In the case of melting of the Ni-Cr-B-Si-C alloy, the cast tungsten carbide particles remain in the solid state. The surface of the tungsten carbide particles dissolves in the melted nickel-chrome alloy. Mutual diffusion of the components occurs, and the amount of carbide eutectic and disperse carbides increases during subsequent crystallization (Figure 7). Being heavier than the melt, the cast tungsten carbide particles descend to the base material surface. The eutectic with participation of iron is formed on the interface with the base material. Simultaneously, thermoreactive dissolution of the steel base occurs and holes are formed under the cast tungsten carbide particles, which improves adhesion between the coating and the base material (Figure 7). The hardness of the cast tungsten carbide particles is very high. The microhardness value determined by a PMT-3 tool with a 50-g load on the indenter was \( H_{50} = 32.36 \) GPa. For comparison, the microhardness of the base material (65G steel) quenched by laser treatment to the martensite state is \( H_{50} = 10.7 \) GPa.

The wear resistance of the resultant composite coating was estimated by dragging it on a fixed abrasive material in accordance with the requirements of the Russian Standard GOST 17367-71. Samples of coatings obtained by means of laser cladding of the PG-10N-01 wear-resistant alloy and of R6M5 high-speed tool steel powder were tested simultaneously. No cracks, flakes, chips, or spalls of the clad material were observed during the tests. The test results are summarized in Table 2.

![Figure 7](image.png)
*Figure 7. The structure of the deposited layer of 55% PG-10N-01 + 45% spherical relit by weight (Upper - surface after abrasive wear, lower - fusion zone).*
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| Coating composition | Hardness | V_{wear}, 10^{-7}, \text{kg/s} |
|---------------------|----------|-------------------------------|
| PG-10N-01           | HRC_{exp} 45 - 48 | 25.0                          |
| R6M5                | HRC_{exp} 66     | 15.6                          |
| PG-10N-01 (55%), cast WC (45%) | H_{50}=32.36 GPa | 4.9                           |

It follows from the data obtained that the wear resistance of the PG-10N-01 alloy in the case of its dragging on a fixed abrasive material increased by a factor of 5 due to additional hardening by cast tungsten carbide with spherical particles. As a result, it became higher than the wear resistance of high-speed steel by more than a factor of 3.

6. Conclusions
The results of the present study revealed the prospects of multilayer cladding of R6M5 high-speed tool steel (analog of M2 steel (USA) and HS6-5-2 steel (EU)) onto low-alloy steel with the use of a laser beam. Controlling thermal cycles of laser cladding, it is possible to obtain a clad coating made of high-speed steel having the structure of high-alloy austenite-martensite mixture with disperse inclusions of carbides up to 10 mm thick, i.e., it is actually possible to create bimetal structures.

The wear resistance of the laser-clad self-fluxing Ni-Cr-B-Si-C alloy in the case of its dragging on a fixed abrasive material increases by a factor of 5 due to additional hardening by cast tungsten carbide with spherical particles. In work [6], it was shown that the abrasive wear of Ni-Cr-B-Si-coatings with WC ceramics of 25% compared to Ni-Cr-B-Si-C without ceramics created by laser cladding according to principle "ball-on-disk" is insignificant at low sliding speed. As a result, it becomes higher than the wear resistance of high-speed steel by more than a factor of 3.

Cast tungsten carbide with spherical particles can be recommended as a component for wear-resistant coatings and clad layers for elements operating under abrasive wear conditions: drilling tools, executive devices of excavating, construction, and road-building machines, clay mixers, elements of metallurgical equipment, etc.

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