Development of laser powder cladding technology for restoration of heat-resistant nickel alloys turbine blades

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Abstract. There is the influence of high temperatures and internal stresses, defects accumulate, which lead to the formation of microcracks of various types, wear and subsequent destruction of the blade during their exploitation. In view of the complexity in the manufacture and high cost of new blades, after the development of their resource, the blades should be restored. This paper shows applying investigation which was directed to make a technological recommendations for restoration cladding of turbine blades. The influence of initial material characteristics and main technological parameters of cladding process on formation of geometry, structure and potential defects of deposited metal is considered. Based on obtained dependencies, criteria that allow producing a defect-free clad with controlled structure and a minimized allowance for further machining are determined. As result of investigation, laser powder cladding technology for restoration of heat-resistant nickel alloys turbine blades is developed.

1. Introduction.

Turbofan engines (TE) are widely used in aviation, energy and other industries with annual demand more than 1200 units. The main consumer of TE is power engineering, where they are used as driving electric power plants of various types, which provide ultimate consumers with electricity and heat. The volume of sales TE in this industry is steadily growing and in 2014 it was $ 22.7 billion USA or 1280 TE. According to forecasts, by 2021 it will be about 27 billion dollars. USA, which is about 1500 TE. TE are widely used in the aircraft industry. In 2011, the world market sales of TE in aircraft construction amounted to 60.1 billion US dollars and according to the projected estimates it should grow by 1.7 times by 2025 and make up 100.8 billion US dollars [1].

The reliability of gas turbine engines is most dependent on the reliability of the compressor and turbine blades, since they are the most loaded parts. TE blades have a complex spatial geometry and are made of hard-deformable high-temperature alloys, the choice of which is determined by the operating temperature of the engine. They have to meet strict requirements such as: by a metal structure, its chemical composition, mechanical properties, the geometric size exclusion defects (forging fold, perforating, metal burning, thermal damage, etc.) [2].
The blades are exposed static, dynamic and cyclic loads, moreover, the turbine blades undergo cyclic and thermal stresses, and they work in corrosive gas environment at a high temperature and subjected to gas corrosion [3]. Under the influence of high temperatures and internal stresses, defects accumulate, which lead to the formation of microcracks of various types, wear and subsequent destruction of the blade. Turbofan engine blades have a lifespan established by the developer (usually 25,000 hours), then the engine is sent for maintenance and subsequent removal of blades from it [4]. In view of the complexity in the manufacture and high cost of new blades, after the development of their resource, the blades should be restored [5].

The simplest and most common method of restoration is argon-arc cladding. This method has a number of negative aspects: due to direct melting of the parent metal by an arc, a significant zone of thermal influence with a coarse-grained structure is formed, which requires subsequent thermal treatment; Edges are formed up to several millimeters for subsequent machining [6].

The most promising technologies in the field of surface engineering are laser technologies, which allow the processing of surfaces without volumetric heating of the part and ensure the achievement of ultra-high speeds of heating and cooling of the laser impact zone due to the high power density in the impact zone [7]. The deposited layer has a fine-grained structure. The size of the heat-affected zone and stock for subsequent machining are within a few hundred microns [8].

2. Methods, materials and equipment.

The powders based on high-temperature nickel alloys ZhS32-VI and EP648 were used as the filler material. The powders were obtained by the Plasma Rotating Electrode Process (PREP) [9] at the Composite JSC, Russia. The chemical composition of the alloys is given in Table 1. Figure 1 shows the type of particles of the powders.

Table 1. Chemical composition of powders for cladding.

| Powder grade | Content of elements, mass.% |
|--------------|-----------------------------|
|              | Ni  | Cr  | Al  | Co  | Ti  | Nb  | Mo  | W   | C   | Ta, Re | Fe |
| ZhS32-VI     | base | 4,3-5,6 | 5,6- | 8,0- | -   | 1,4- | 0,8- | 7,7- | 0,15 | 3,5-   | <1,0 |
| (CMSX-4)     |     | 6,3  | 10,0|     |     | 1,8 | 1,4 | 9,5 |     |        | 4,5 |
| EP648        | base | 33,97 | 1,03| -   | 0,98| 0,87| 2,6 | 4,43| 0,04 | -      | 0,36 |

Figure 1. The type of powder particles: a) ZgS-32-VI; b) EP648.

Experimental research was done on laser cladding technological machine (figure 2) based on industrial robot LRM-200iD_7L, Fanuc; laser irradiation source LK-700, IPG Photonics; laser head FLW D30, IPG Photonics with removable cladding nozzle COAX-40-S, Fraunhofer ILT; powder
feeder Oerlikon Metco Powder Feeder Twin 150 with track transection of metering disk of 5×0.6 mm².

Longitudinal and transverse sections were used to study the microstructure of the samples. To reveal the structure, the surface of polished sections was etched using nitromuriatic acid. Metallographic studies were carried out using an optical microscope DMI 5000 (Leica) and a scanning microscope Phenom ProX.

3. Results and discussion.

The dependence of powder utilization rate on area of molten pool and diameter of gas-powder jet, and also condition of stable formation during multilayer cladding was investigated in previous study [10]. During the current task of this investigation’s part the granulometric composition influence to thin-wall cladding formation was established.

The walls were built-up from powders separated to different fractions. Figures 3 and 4 shows the average layer height and formation types of cladded wall, respectively.

The width of deposited walls, and hence the approximate diameter of molten pool, is 1.2 mm. Due to the constancy of molten pool area, the powder utilization rate is reduced due to increasing diameter of the gas-powder jet caused by increasing of particle size. To explain the regularity of powder utilization rate decreasing with increasing of powder granulometric composition, the initial characteristics of each fraction were investigated. As a result of the study it was found that all separated powder fractions have a spherical shape and almost the same bulk density. The only
characteristic which changes proportionally to varying particle size is powder flowability is established (figure 5).

![Graph showing the dependence of powder flowability and its granulometric size.](image)

**Figure 5.** The dependence of powder flowability and its granulometric size.

After determining the characteristics of gas-powder jets and their influence on formation of cladding influence of irradiation power, laser beam traverse speed and feeding rate on formation of geometry, structure, and potential defects during laser cladding of heat-resistant nickel alloys were investigated.

As a result of cladding dimensions measurement, the following regression dependences for the width and height of the deposited beads were established:

\[
B = -0.00001P^2 + 0.0098P - 0.0002V^2 - 0.0014V + 0.0258F^2 - 0.2858F + 0.1012, \quad (1)
\]

\[
H = -0.000004P^2 + 0.0022P + 0.0003V^2 - 0.0291V - 0.0072F^2 + 0.1624F + 0.2682, \quad (2)
\]

where \( P \) is laser power, W; \( V \) – traverse speed, cm/min; \( F \) – feeding rate, g/min.

Metallographic studies have shown that the microstructure of the cladded metal is predominantly columnar grains or oriented along the temperature gradient direction, in accordance with direction of laser beam movement. Depending on the local cooling conditions, deviations from the primary directions are possible. But because of geometric selection, the growth of such crystals quickly ceases. Typical structures of polished transverse and longitudinal sections are shown in figure 6.

![Metallographic images showing transverse and longitudinal sections of cladding](image)

**Figure 6.** Typical microstructure of transverse (a) and longitudinal (b) sections of cladding

Equiaxed crystals were found in all the specimens besides the columnar ones. As is known from crystallization theory, columnar crystals with degenerate second arms are formed under high temperature gradients \( G_t \) conditions. Their growth proceeds in direction of preferential heat flow.
During crystallization front moves and crystallized layer increases, the temperature gradient decreases significantly. The formation of secondary arms becomes possible, and the growth direction approaches the crystallographic direction <001> [11]. During a further temperature gradient decreasing and the appearance of concentration supercooling, the columnar to equiaxed transition (CET) occurs. Figure 7 shows the dependence of primary structure type on the temperature gradient and the crystallization rate.

CET can only be determined from the last bead, since in the previous layers the region of equiaxed crystals is re-melted down to the columnar ones due to the imposition of subsequent passes. The ratio of directional crystallization section area to total melt area per pass was criterion for estimating the effect of technological parameters on bead microstructure (fig. 8).

According to the results of statistical analysis, the regression equation for the ratio of directional crystallization section area to total melt area, depending on cladding parameters, takes the following form:

\[
\frac{S_{\text{HK}}}{S_{\text{total}}} = -0.00002P^2 + 0.0002P + 0.00009V^2 - 0.0138V - 0.0004F^2 + 0.0428F + 0.5514, \tag{3}
\]

where P is laser power, W; V – traverse speed, cm/min; F – feeding rate, g/min.

According to the results of the metallographic study, in a number of samples cracks are found, which are predominantly along the grain boundaries of the cladded metal (fig.9b). Fractographic analysis revealed the presence of interlayers in fracture (Figure 9 d). Probably in the defective samples there is grain boundary segregation of chemical elements, which leads to hot cracks in the process of welded metal crystallization.
Comparing the structure and cladding regimes, it is established that the appearance of cracks is affected by all three parameters expressed by the complex value of the amount of energy per deposited metal. We reduce them to two values: heat input (J / mm) and the feeding rate per distance (g / mm) for display capabilities of three process parameters in a two-coordinate system. Let's construct a graph where x-axis is heat input, y-axis is a feeding rate per distance, we plot the points of the investigated deposition regimes (figure 10). For clarity we introduce two types of points, showing the presence (red dots) and absence (blue) cracks.

Figure 9. Longitudinal sections of welded samples: a) qualitative regime, there are no macrodefects, b) a regime leading to the formation of cracks, c) a crack, and d) fracture of crack
Comparing the crystallization conditions with crack formation in the cladding, the influence of temperature gradient and crystallization rate on the absence or presence of cracks was revealed. Figure 11 shows a diagram describing the type of primary crystalline structure with marked areas, showing the presence and absence of cracks.

As follows from figure 11, the tendency to crack formation in the cladding increases when temperature gradient and crystallization rate increase. As is known, the temperature gradient directly affects the internal thermal stresses. Because of the high crystallization front velocities, elements with a low solidus temperature do not have time to diffuse into the far-away regions of the molten pool. It leads to the liquid interlayer formation between the grains of the crystallized metal. Both these factors, in combination with structural stresses, can lead to the formation of cracks [13].

Figure 10. The experimental dependence of the absence / presence of cracks in the weld metal depending on the process parameters.

Figure 11. Diagram of microstructure type dependence on the temperature gradient and the rate of crystallization, with placed areas corresponding to experimental samples with the presence and absence of cracks.

Figure 12. Cladded turbine blade top edge: a) general view, b) digitized image, c) luminescent control, d) microphotography of cross-section.
4. Conclusions.

1. The irradiation power, traverse speed of laser beam and the feeding rate have a different effect on the formation of bead geometry, structure and the defect-free cladding. Comparing the character of technological parameters influence, the expediency of controlling the obtaining cladding properties by changing the laser beam traverse speed is established. Traverse speed decreasing leads to:
   • increasing bead height reduces the temperature gradient of the melt. As result welding stresses should be lower;
   • lower traverse speed reduces the maximum crystallization rate. This avoids the formation of liquid interlayers in crystallized metal;
   • area of directed crystallization section of will be increased;
   • surface of molten pool will increase. This will allow transferring to clad for more filler powder and increase the height of the bead.
2. Increasing the powder flowability leads to an improvement of the nozzle focusing ability and flow constancy of filler material. In turn, the bead height increases.
3. The height of bead not only positively affects the metal structure that forms, but also increases the productivity of the cladding process.
4. Analyzing the obtained dependencies, technological recommendations are proposed for further restoration cladding of turbine blades. Based on these recommendations, laser cladding technology for restoration of blades from heat-resistant nickel alloys was developed and introduced at the production in JSC "UEC-Perm Motors". Figure 12 shows the results of geometry restoration of turbine blade top edge from alloy ZhS32-VI obtained by this technology.

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