The features of surface composite layer formation by laser-powder treatment of steel with tungsten carbide particles

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Abstract. The laser-powder melt injection of WC particles into the steel matrix for locomotive wheels surface hardening was discussed. Calculations shown that the process parameters and sizes of injected particles determine the interaction between the particle and the metal matrix of the composite layer. In studied samples small particles surface melting was observed, while some large particles were centers of crystallization for the melted steel. Tungsten concentration in the steel matrix is high in regions with small WC particles, we can assume it is the result of the tungsten diffusion from WC particles overheated by the laser beam. These phenomenon makes the steel microstructure inhomogeneous and further investigations are necessary to determine its influence on the part properties.

1. Introduction
The railway transport has a priority in cargo transportation in Russia. In 2017 its part in trucking was 45.5%, and therefore the cost of locomotives operation has a significant influence on the economy of the country.

For railway transport machines manufacturers, one of the most important tasks is increasing of parts resource. Wear decreasing in wheel-rail system has a particular importance for locomotive wheels, because high transfer of effort needed to a train movement makes it difficult to decrease friction. That means performance characteristics of materials used are to be improved.

The plasma quenching process is a wide-spread method for wheel rims in Russia, it provides the increase of hardness up to 800 HV, and therefore wear resistance of quenched wheels is up to 3 times higher. Nevertheless, wheel lifetime still limits service interval of locomotives, reducing their operation efficiency.

The application of expensive wear-resistance materials in the large-scale production is economically unreasonable, in the same time there is no possibility for the significant wheel lifetime prolongation by surface hardening of traditional materials.

In this work, some scientific and technical aspects of locomotive wheel rims surface layers hardening by the laser-powder injection of WC particles are discussed.

The analysis of available literature data shown that this process is less investigated compared with the cladding process and its applicability for railway wheels is not studied.

The results of investigations [1, 2, 3] of the plasma-powder WC injection into the steel matrix shown that this method provides significant wear decreasing, but usage the plasma as the power source for the metal melting requires the WC powder injection into the back of the weldpool to avoid particles melting [4]. In the same time, coaxial feeding results in deeper WC penetration. Another way is the laser-powder processing application [5, 6] for creating surface composite layers steel/WC.

The experience in laser cladding of NiCrBSi/WC composites and the analysis of available literature sources [7, 8] lead to choose the spherical WC powder with the main fraction from...
80 to 100 µm. However, there is not enough data about the influence of the size of a particle on its interaction with the steel matrix.

The aim of the present study was the investigation of features of the different size particles laser-powder injecting into the steel matrix.

2. Materials and equipment
The samples were made of the mark 2 steel according to GOST 398-2010, which is commonly used for locomotive wheels manufacturing. Its chemical composition is presented in Table 1. WC particles were injected into the steel melted by the laser beam, the properties of the powder are presented in Table 2. The IPG-Photonics fiber laser YLS-5 with the cladding head was applied in experiments. The coaxial powder feeding was used.

| Element | Fe | C | Si | Mn | P | S | Cr | Other |
|---------|----|---|----|----|---|---|----|-------|
| Wight conc., % | 97.97 | 0.599 | 0.36 | 0.859 | 0.0091 | 0.0053 | 0.094 | 0.1016 |

Table 2. The properties of the WC powder

| Item                  | Value                                      |
|-----------------------|--------------------------------------------|
| Shape                 | Spherical                                  |
| Range of diameters    | From 40 to 180 µm                          |
| Prevailing fraction   | From 90 to 150 µm                          |
| Chemical composition  | C – 3.9 %, Fe – 0.9 %, Other – 0.2 %; W – balance |

3. WC particles heating modeling
In contrast to the cladding process, the powder melting is undesirable in the laser-powder injection process. In that case when metal evaporation is avoided, the temperature of the melted steel is lower than the WC melting point. However, the laser beam heats WC particles and the evaluation of their temperature is necessary to define the possibility of their melting. A simple calculation can be made in case we assume the following:

- the particles are irradiated only on the last part of the way to the sample surface because of geometrical features of the powder feeding system;
- on the last part of the way the laser beam diameter equals the diameter of the flow of the powder and they can be considered as constant;
- the power density distribution along the fiber laser beam cross-section in the considered part of the beam trajectory is homogeneous;
- all of the particles have the same diameter and the same velocity;
- the average absorption coefficient of WC particles is assumed to be 0.3, though in practice it depends on the particle surface temperature;
- the temperature in different parts of a particle is the same because of its small size and because the heating is applied from different sides.

The equation for a particle temperature is given by the Equation 1:
\[ T_{WC} = \frac{Q_l}{c_{WC} \cdot \gamma_{WC} \cdot V_{WC}}, \]  

(1)

Where \( Q_l \) is the energy absorbed by the particle, J; \( c_{WC} \) is specific heat of WC, J·kg\(^{-1}\)·K\(^{-1}\); \( \gamma_{WC} \) is the WC density, kg·m\(^{-3}\); \( V_{WC} \) is a particle volume, m\(^3\).

The energy absorbed by a single particle is calculated according the Equation 2:

\[ Q_l = A_{WC} \cdot P_l \cdot \tau \cdot \frac{S_{WC}}{S_l}, \]  

(2)

Where \( A_{WC} = 0.3 \) is the coefficient of absorption; \( P_l \) is the laser beam power, W; \( \tau \) is a particle irradiation duration, s; \( S_{WC} \) is the area of a particle central cross-section, m\(^2\); \( S_l \) is the laser beam cross-section area, m\(^2\).

A particle irradiation duration is given by the Equation 3:

\[ \tau = \frac{h_{WC}}{v_{WC}}, \]  

(3)

Where \( h_{WC} = 0.001...0.003 \) m is the distance on which a particle is irradiated; \( v_{WC} = 5...10 \) m/s is WC particles velocity. In this work, \( h_{WC} = 0.002 \) m according to experimental data.

The specific heat depends on the temperature. The linear approximation of the \( c_{WC}(T) \) function can be given by the Equation 4:

\[ c_{WC}(T) = 0.419 \cdot T + 200,28 \]  

(4)

The summary of values used for calculations is presented in Table 3.

| Item                                      | Value                                      |
|-------------------------------------------|--------------------------------------------|
| WC specific heat, \( c_{WC} \)            | \( c_{WC}(T) = 0.419 \cdot T + 200,28 \) (J·kg\(^{-1}\)·K\(^{-1}\)) |
| WC particles diameters range               | From 50 to 150 µm                          |
| The length of the track on which particles are irradiated | 0,002 m                                    |
| Laser power density, \( P_l/S_l \)        | \( 2.83 \times 10^8 \) W·m\(^{-2}\) and \( 4.95 \times 10^8 \) W·m\(^{-2}\) |
| Absorption coefficient, \( A_{WC} \)      | 0.3                                        |
| WC density                                | 15670 kg·m\(^{-3}\)                       |

The melting point of WC is 3143 K, if the calculated temperature is higher than this value it means that the particle is partly melted.

The results of calculations are presented in Figure 1.

From the graphs (Figure 1) we can see that the same process parameters lead to different states of the injected particles with different sizes:

- small particles (the diameter less than 60 µm) at realized parameters of the laser-powder treatment can be partly melted by the laser radiation;
- medium particles with the diameter less than 100 µm can have temperature higher than the melted steel, thus they can increase the energy content of the melted metal;
- large particles with the diameter above 100 µm are almost always colder than the melted steel, and in some cases, they can have temperature lower than the steel melting point.

![Figure 1](image)

**Figure 1.** Calculated temperatures of WC particles, the power density of the laser radiation is $2.83 \times 10^8$ W·m$^{-2}$ (a) and $4.95 \times 10^8$ W·m$^{-2}$ (b)

Based on the calculation results we can conclude that WC particles with different sizes have different effects on the structure of the steel matrix; while relatively cold large particles can act as centers of crystallization, hot small particles have temperature high enough for the diffusion processes intensification [9]. In the same time, all of them effect the thermal cycle of the steel laser treatment process.
4. **Investigation of matrix microstructure near WC particles**

The remelted metal has dendritic structure. The structure near WC particles differs from the one far from them. Around a relatively large particle (Figure 2a) the dendrite structure becomes more dispersed; the primary dendrite axes are mainly oriented perpendicular to the particle. Between two large particles (Figure 2b) the cellular-dendritic structure is observed.

![Figure 2a](image1)

**Figure 2a.** The matrix microstructure near the large WC particle

![Figure 2b](image2)

**Figure 2b.** The matrix microstructure near the large WC particle (a) and between two large WC particles (b)

On the photo (Figure 3) the partly melted small WC particle is observed.
In general, the observed structures changes correspond to the expected ones on the basis of the calculation results analysis. The chemical composition study in the area with a lot of small WC particles confirms the assumption about diffusion processes intensification. The results of measurements carried out with the use of characteristic radiation on the electron microscope are presented in Figure 4. High W concentration affects the steel properties, in particular increased mechanical properties can be achieved. Nevertheless, in some cases it can decrease the steel corrosion resistance.

![Figure 3. The partly melted WC particle](image)

**Figure 3.** The partly melted WC particle

| Element Symbol | Atomic Conc. | Weight Conc. |
|----------------|--------------|--------------|
| Fe             | 86.39        | 66.78        |
| W              | 12.82        | 32.61        |
| Mn             | 0.80         | 0.61         |

![Figure 4. The results of the chemical composition analysis (point 2)](image)

**Figure 4.** The results of the chemical composition analysis (point 2)

In general, the tungsten diffusion causes the inhomogeneous chemical composition distribution in the remelted metal, which results in the heterogeneity in all other properties. The influence of this phenomenon on the hardened surface layer performance is to be studied.

5. Conclusions
On the basis of investigations carried out, the following conclusions can be made:
• when WC particles are injected into the melted metal by the laser-powder treatment, the changes of the matrix microstructure depend on process parameters and particle sizes;
• small particles increase the energy of the melted metal, they can also be partly melted and tungsten can diffuse into the steel matrix;
• large particles can act as crystallization centers and cause the dispersing of the dendritic structure of the matrix.

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