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The Effect of Laser Post-Processing on NiCrMoSiBFeCuC Thermally Sprayed Coatings

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AbstractDuring the study, a nickel–chromium-based coating was formed on structural steel S235 using flame spraying technology. A NiCrMoSiBFeCuC powder mixture with the following composition was used for coating formation: ~67% Ni; 0.45% C; 4.11% Si; 3.92% B; 2.72% Fe; 15.7% Cr; 1.94% Cu; 4.69% Mo. The sprayed coatings were remelted using a gas torch at a temperature of 1100 °C in air. At the next stage of coating formation, the samples were processed with a fiber laser under four processing speed modes - without beam oscillation and with oscillation amplitudes of 1 mm and 3 mm. The aim of this study was to investigate the effect of laser processing on NiCrMoSiBFeCuC coatings formed by spraying followed by gas torch remelting. The shape and geometry of the laser-remelted tracks, microhardness of the samples, as well as tribological properties and wear resistance were investigated. The combined method of coating formation, including spraying followed by laser treatment, allows the formation of a continuous or localized NiCrMoSiBFeCuC coating layer with increased microhardness and wear resistance on the surface of the component.

Keywords: thermal spray, NiCrMoSiBFeCuC coating, laser post-processing, hardness, tribology

Introduction

The application of sprayed coatings in industry makes it possible to improve the surface properties of components both during manufacturing and repair. Thermally sprayed coatings based on nickel-chromium-molybdenum-silicon-boron (NiCrMoSiB) are one of the most popular classes of protective coatings, widely used in mechanical engineering, energy, oil and gas, and chemical industries. Their popularity is due to the combination of high wear resistance, corrosion resistance, and the ability to operate at elevated temperatures and in aggressive environments [1].

These coatings are based on a nickel matrix alloyed with chromium, molybdenum, silicon, and boron. Chromium provides high corrosion and oxidation resistance, molybdenum improves mechanical strength and wear resistance, while boron and silicon contribute to the formation of a eutectic structure and reduce the melting temperature of the alloy. This is especially important for subsequent remelting of the coating, which makes it possible to obtain a dense, low-porosity structure with good adhesion to the substrate [2].

The most common methods for producing NiCrMoSiB coatings include flame spraying, plasma spraying, and high-velocity oxy-fuel (HVOF) spraying [3–4]. After spraying, the coatings are often subjected to remelting (e.g., flame or laser remelting), which reduces porosity, eliminates interparticle bonding defects, and results in a more homogeneous structure. As a result, the mechanical and operational properties of the coating are significantly improved [5–6].

NiCrMoSiB coatings are widely used for components operating under friction and wear conditions, such as shafts, bushings, pump elements, valves, as well as components exposed to corrosive environments. Their application is particularly effective in the restoration of worn surfaces, allowing the service life of expensive components to be extended and reducing maintenance and replacement costs.

One of the key directions of modern research is the use of laser processing of sprayed coatings. Laser remelting enables localized treatment of the surface, providing high energy density and precise control of process parameters. This promotes the formation of a fine-grained microstructure, increases microhardness, and improves tribological properties. However, certain challenges arise, such as crack formation due to high thermal gradients, which requires optimization of processing parameters [7].

The prospects for the development of NiCrMoSiB coatings are associated with the improvement of deposition technologies and subsequent processing methods. Particular attention is given to combined approaches, including spraying followed by laser or electron beam remelting. In addition, modification of powder compositions through the introduction of reinforcing phases (carbides, borides) is actively investigated, which allows further enhancement of wear resistance and thermal stability of the coatings [8–13].

Thus, NiCrMoSiB-based coatings have significant potential for further application and development. Their unique combination of properties makes them promising for use under conditions of intensive wear, corrosion, and high temperatures. Further research aimed at optimizing composition, structure, and processing technologies will enable an even broader range of applications and improved efficiency of engineering systems.

1. Methodology of experimental investigation

The coatings were formed on low-carbon structural steel S235 (according to EN 10027-1) plates. The dimensions of the cut plates were 100 × 100 × 10 mm. The S235 steel plates were coated with nickel–chromium-based powders, the chemical composition of which is presented in Table 1. This coating is used in applications where corrosion and wear resistance are required.

Table 1. Chemical composition of NiCrMoSiBFeCuC powder, %

Ni–Cr–Co–Si–B–Fe–Cu–C composition							
Ni	Cr	Mo	Si	B	Fe	Cu	C
Bal.	15,7 %	4,69 %	4,11 %	3,92 %	2,72 %	1,94 %	0,45 %

Before thermal spraying, the plate surfaces were prepared by chemical and mechanical cleaning. Prior to the coating process, in order to improve coating formation conditions, the plate surfaces were preheated with a neutral acetylene–oxygen flame to a temperature of 250 °C.

A two-stage technology was used for the production of sprayed and remelted coatings: powder deposition followed by remelting of the deposited coating using a flame. In this study, spraying parameters were selected according to the equipment manufacturer's recommendations and further refined during trial spraying (Table 2). The final thickness of the sprayed coating was ensured by selecting an appropriate number of deposited layers. To ensure the stability of the technological process parameters during the experiment, an industrial robotic manipulator Motoman 100 MH6 was used.

Table 2. Main parameters of coating formation processes

Substrate preheating	Neutral flame C_2H_2/O_2 ~250°C
Thermal spray flame	Neutral flame 0,07 MPa C_2H_2/ 0,4 MPa bar O_2
Spraying distance	170 mm
Spray speed/step/layer	250 mm/s /5 mm / 8 layers
As-sprayed layer thickness	1,2– 1,4 mm
Remelted flame	Neutral flame 0,035 MPa C_2H_2/ 0,4 MPa O_2
Remelted temperature	1100^0C
Cooling	In air, at a temperature of 22°C
As-sprayed and flame remelted layer thickness	0,940–1,010 mm

For laser treatment of the flame-sprayed and remelted coating samples, a 1500 W FANUCI PRO laser with a continuous-wave fiber laser source and beam oscillation function was used. The laser beam wavelength was 1070 nm. The main parameters were as follows: laser power – 375 W; oscillation – sinusoidal with a frequency of 110 Hz; laser beam diameter – 1 mm; laser processing speed varied from 500 to 1250 mm/min; oscillation amplitude – 0, 1, and 3 mm; shielding gas – argon; shielding gas flow rate – 15 L/min. The laser processing parameters of the flame-sprayed and remelted coatings are presented in Table 3.

Table 3. The main parameters of laser processing of samples

Laser processed speed, mm/s	Laser beam oscillation, mm		
	0	1	3
500	X	X	X
750	X	X	X
1000	X	X	X
1250	X	X	X

The morphology and geometry of the tracks of the sprayed, flame-remelted, and laser-processed coatings were investigated using optical macroscopy. For this purpose, the samples were sectioned and metallographic cross-sections were prepared. The samples were ground using abrasive papers of different grit sizes from P240 to P2500. After grinding with P2500 paper, the surfaces were polished using polishing pastes with particle sizes ranging from 3 to 0,2 µm. After polishing, the samples were cleaned in an ultrasonic bath using an acetone solution and then dried with a stream of hot air.

The microhardness of the investigated samples was measured on polished cross-sections using a Mitutoyo HV-100 automated microhardness tester. The maximum measurement error was 1%. Measurements were performed using the Vickers microhardness method with a load of 200 g and a dwell time of 15 s. The optical magnification of the obtained microhardness indentations was 50X. The average microhardness of the samples was calculated from ten measurements, excluding the minimum and maximum values.

The tribological properties (coefficient of friction) and wear resistance of the investigated samples were evaluated using a dry sliding test with a Microtest tribometer. The tests were carried out using the "ball-on-disc" configuration. The following experimental parameters were used: test temperature – 21 °C, load – 30 N, sliding distance

– 100 m, rotational speed – 200 rpm, and track radius – 1 mm. A 6 mm diameter hardened AISI 52100 steel ball was used as the indenter.

The wear resistance of the samples was evaluated by comparing the mass changes before and after the wear tests. The wear resistance was calculated based on the results of two tests. To reduce inaccuracies in the friction coefficient measurements, the initial stage of the test (the first 20 m) was excluded from the analysis. The wear rate of the samples was determined using the weighing method with an analytical precision balance RADWAG AS60/220.R2, with an accuracy of ±0.01 mg.

2. Results and Discussions

To evaluate the effect of laser treatment and its parameters on the remelting process of the NiCrMoSiBFeCuC coating, a macroscopic analysis of the processed samples was performed during the experimental investigation. Metallographic cross-sections of the processed coatings were prepared for the study. The sample cross-sections were ground, polished, and cleaned in an ultrasonic bath.

The macroscopic analysis of the remelted coating structure showed that the depth and width of the remelted layer depend on the laser processing speed and the beam oscillation amplitude. The lower the laser processing speed, the deeper the coating is remelted (Fig. 1). This occurs due to a higher energy input into the coating surface during laser treatment. Increasing the laser processing speed of NiCrMoSiBFeCuC coatings from 500 to 1250 mm/s reduces the depth of the formed track in the central region by 1,24–2,0 times, depending on the laser beam oscillation (Fig. 2). The most significant reduction in remelted depth was observed when using beam oscillation amplitudes of 1 mm and 3 mm (1,85 and 2,0 times, respectively).

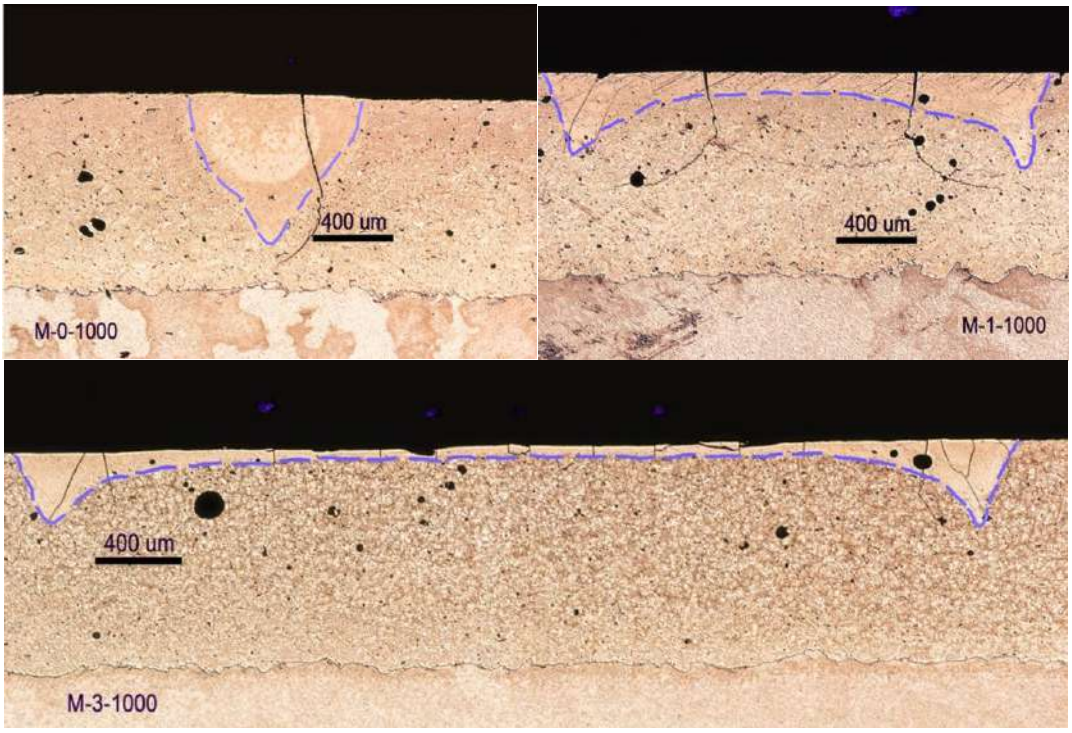

Fig. 1. - Cross-sectional micrographs of molten pools processed with 1000 mm/min laser speed and a varying oscillated amplitude between 0 and 3 mm (M-0-1000 - no oscillation; M-1-1000 - oscillation amplitude 1mm; M-3-1000 - oscillation amplitude 3 mm)

During the macroscopic analysis of laser-treated NiCrMoSiBFeCuC coatings, it was observed that when applying a laser processing mode without beam oscillation (0 mm oscillation), the shape of the remelted track is parabolic. In contrast, with beam oscillation amplitudes of 1 mm and 3 mm, the remelted track exhibits a non-uniform depth, characterized by a flatter central region of the melt pool and deeper sides following a Gaussian-type profile. It was also observed that during laser processing with beam oscillation, the depth of the remelted track in the central region is smaller than at the edges of the track (Fig. 1). This can be explained by the non-uniform distribution of laser energy on the coating surface when using processing modes with beam oscillation.

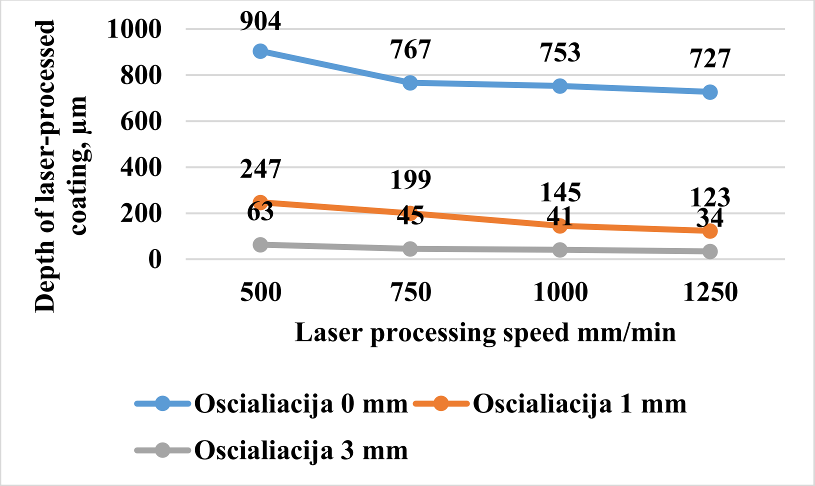

Fig. 2. - The relationship between the depth of molten pools and laser processing speed, applied oscillation amplitude (0 mm - no oscillation; 1mm - oscillation amplitude 1 mm; 3 mm - oscillation amplitude 3 mm)

During remelting of coatings both without and with beam oscillation, the width of the remelted tracks depends on the laser processing speed and the beam oscillation amplitude. Increasing the laser processing speed from 500 to 1250 mm/min reduces the width of the remelted tracks by approximately 1,06–1,88 times (Fig. 3). The most significant reduction (about 1,88 times) is observed when processing the coatings without beam oscillation (0 mm oscillation).

When beam oscillation amplitudes of 1 mm and 3 mm are applied during laser processing, the width of the remelted tracks increases by approximately 1,7–1,9 and 2,9–5,1 times, respectively, depending on the laser processing speed. The largest increase in track width (about 5,1 times) was observed when using a 3 mm beam oscillation at a laser processing speed of 1250 mm/min.

To evaluate the effect of laser processing on the mechanical properties of NiCrMoSiBFeCuC sprayed coatings, the microhardness of the substrate, the as-sprayed and remelted coating, and the laser-processed coating was measured using the Vickers method. The microhardness results showed that, during remelting of the coatings both with and without beam oscillation, the microhardness of the remelted track metal depends on the laser processing speed. Increasing the laser processing speed from 500 to 1250 mm/min increases the microhardness of the remelted tracks by 1,19 to 1,62 times, depending on the beam oscillation amplitude (Fig. 4).

The increase in microhardness of the laser-processed coating metal may be attributed to faster cooling rates, more intensive melt crystallization, a potentially finer microstructure of the remelted layer, and the formation of dispersed phases. The highest increase in microhardness of the remelted coating metal (about 38%) was observed when laser processing the NiCrMoSiBFeCuC sprayed coating without beam oscillation (Fig. 4).

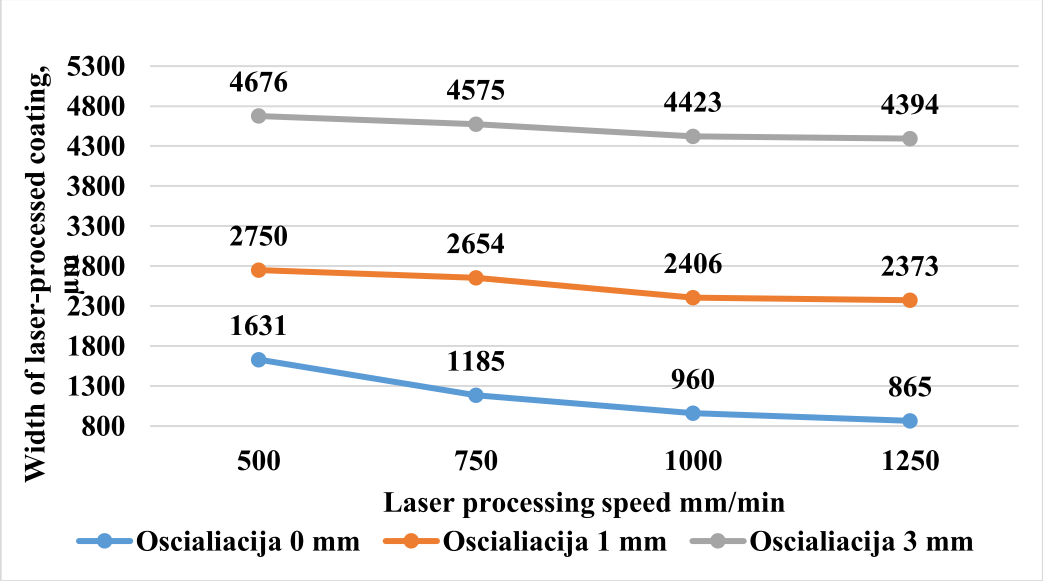

Fig. 3 - The relationship between the width of molten pool and laser operating speed, applied oscillation amplitude (0 mm - no oscillation; 1mm - oscillation amplitude 1 mm; 3 mm - oscillation amplitude 3 mm)

Analysis of the microhardness results showed that the microhardness of the as-sprayed and remelted coating is approximately four times higher than that of the S235 substrate (about 141 HV0.2). During laser processing of the NiCrMoSiBFeCuC sprayed coating, higher processing speeds and lower beam oscillation amplitudes result in higher microhardness of the remelted coating metal. The highest microhardness of the treated coating was achieved at a laser processing speed of 1250 mm/min and a beam oscillation amplitude of 1 mm, reaching 1057 HV0.2. This value is approximately 7,5 times higher than that of the substrate and about 1,9 times higher than that of the as-sprayed and remelted (non-laser-processed) coating (approximately 566 HV0.2).

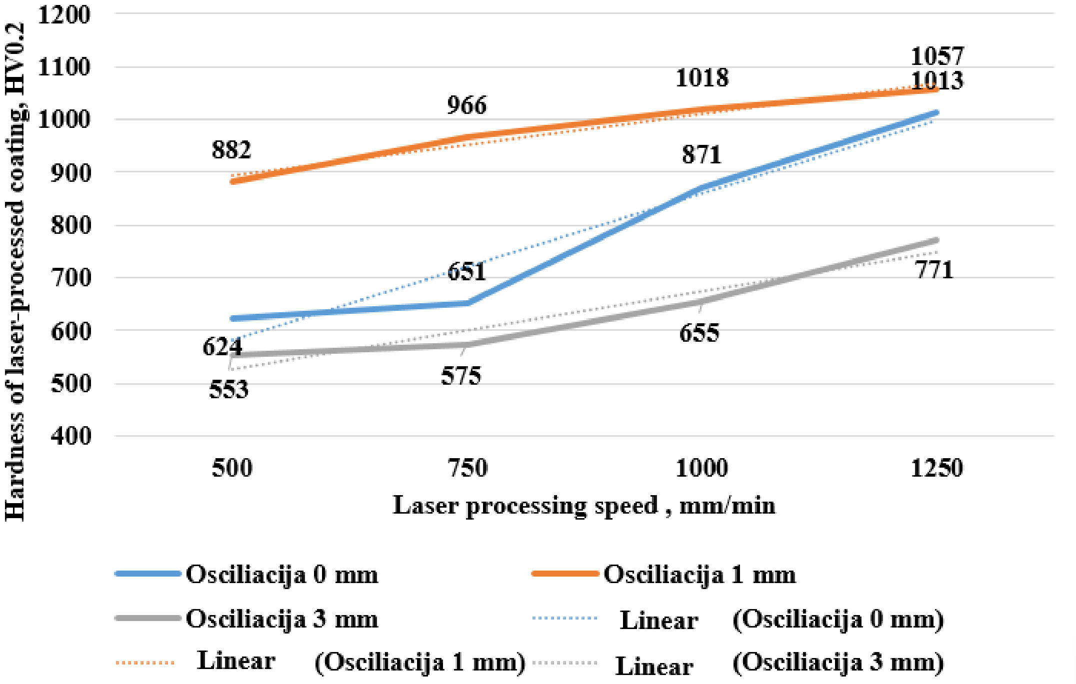

Fig. 4. - The relationship between the hardness of the coating processed at different parameters and laser operating speed, applied oscillation amplitude (0 mm - no oscillation; 1 mm - oscillation amplitude 1mm; 3 mm - oscillation amplitude 3 mm)

One of the most effective methods for evaluating the performance characteristics of a metallic surface operating under frictional conditions is wear resistance testing. To assess the tribological properties and dry sliding wear resistance of the NiCrMoSiBFeCuC sprayed coating after laser processing, a “ball-on-disc” wear test was selected. The results of the tribological and wear tests of the investigated samples are presented in Table 4.

Analysis of the tribological test results showed that the average coefficient of friction of the as-sprayed and remelted (non-laser-processed) coating is approximately 1,5 times higher than that of the substrate. Laser treatment of the coating reduced the average coefficient of friction by about 16%; however, it still remained about 1,27 times higher than that of the substrate. The lower friction coefficient values of the substrate can be explained by the lower strength and hardness of S235 steel. During wear, the softer substrate material promotes better running-in of the tribological contact surfaces.

The wear test results showed that the wear resistance of the as-sprayed and remelted NiCrMoSiBFeCuC coating is approximately 2,65 times higher than that of S235 steel, while the laser-processed coating exhibits about 8,43 times higher wear resistance compared to the substrate. Laser treatment increased the wear resistance of the remelted coating by approximately 318 %. These results indicate that laser processing of NiCrMoSiBFeCuC sprayed coatings significantly improves their operational performance.

Table 4. Results of the tribological tests

Sample	Average coefficient of friction (slip distance 20-100 m)	Sample mass loss (slip distance 100 m), µg	Sample abrasion rate, µg/m	Abrasion resistance of the specimen, m/mg
Steel S 235	0,3315	1180	118	84,7
As-sprayed and flame-remelted coating	0,4990	445	44,5	224,7
Laser processed coating	0,4205	140	14	714,2

Conclusions

The results obtained allow us to draw the following main conclusions:

1. During laser remelting of NiCrMoSiBFeCuC sprayed and flame-remelted coatings with and without beam oscillation, the width and depth of the remelted tracks depend on the laser processing speed and the beam oscillation amplitude. Increasing the laser processing speed leads to a decrease in both the width and depth of the remelted tracks. Introducing beam oscillations of 1 mm and 3 mm increased the track width by approximately 1,7–2,7 and 2,9–5,1 times, respectively, while the maximum remelted depth decreased by approximately 1,5–1,9 and 2,3–2,5 times, depending on the laser processing speed.
2. Macroscopic analysis of the laser-processed coatings showed that, without beam oscillation, the remelted track has a parabolic shape. When beam oscillation amplitudes of 1 mm and 3 mm are applied, the remelted track exhibits a non-uniform depth, with a flat central melt pool region and deeper sides following a Gaussian-type profile.
3. During laser remelting at processing speeds of 500–1250 mm/min without preheating, cracks formed in all samples. The introduction of beam oscillation during processing increased the number of cracks.
4. Microhardness measurements showed that the microhardness of the remelted tracks depends on the laser processing speed, both with and without beam oscillation. Increasing the laser processing speed from 500 to 1250 mm/min increased the microhardness of the remelted coating by 1,19 to 1,62 times, depending on the beam oscillation amplitude, due to faster cooling of the coating material. The highest microhardness of the treated coating (1057 HV0.2) was achieved at a laser processing speed of 1250 mm/min and a beam oscillation amplitude of 1 mm. This value is approximately 7,5 times higher than that of the substrate and about 1,9 times higher than that of the as-sprayed and remelted coating.
5. Analysis of the tribological test results showed that the average coefficient of friction of both as-sprayed and laser-processed coatings is higher than that of the substrate by approximately 1,5 and 1,27 times, respectively. The lower friction coefficient of the substrate can be explained by the fact that the softer substrate material promotes better running-in of the tribological contact surfaces during wear.
6. The wear test results showed that the wear resistance of the as-sprayed and remelted NiCrMoSiBFeCuC coating is approximately 2,65 times higher than that of S235 steel, while the laser-processed coating exhibits about 8,43 times higher wear resistance than the substrate. It can be concluded that laser treatment increases the wear resistance of the remelted coating and improves its service performance.

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