

Article

Effect of Partial Fibre Laser Processing on the Wear Resistance of NiCrMoFeCSiB Coatings

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Abstract: Surface laser processing of metallic materials is known to be effective in improving wear resistance due to microstructure refinement and the associated hardening effect. However, the formation of cracks, which frequently accompanies such processing, remains a challenge. This work focusses on partial laser processing of Ni-based protective coatings as a method that could potentially reduce the risk of crack formation due to lower overall heat input and retaining softer material portions that facilitate stress redistribution. A fibre-optic laser with a wavelength of $\lambda = 976$ nm and beam oscillation capability was used. After laser processing at 175 W power, a 250 mm/min processing rate, and a 2 mm oscillation amplitude, coating hardness increased by ~ 1.49 times reaching 713 ± 19 HV0.2 value. Preheating the samples to 400 °C inhibited crack formation but partially reduced the quenching effect, providing a $\sim 30\%$ increase in coating hardness (631 ± 16 NV0.2). The resistance to dry sliding wear was increased by ~ 2 times and to abrasive wear—by ~ 2.9 times. Partial laser treatment of 25%, 50%, and 75% of the surface area enhanced the coating's wear resistance by 1.29, 2.13, and 2.81 time, respectively, indicating that when the processed surface area reaches 50% or more, wear resistance is primarily determined by the hardened regions and to a greater extent than what is expected based on the proportion of the treated area.

Keywords: surface laser processing; Ni-based coating; fibre laser; laser oscillation; tribology; effectiveness



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1. Introduction

In recent decades, multicomponent coatings deposited by thermal spray methods have attracted considerable attention due to their excellent performance characteristics such as high hardness, adhesion strength, corrosion resistance, good ductility, and resistance to brittle fracture [1–4]. However, ensuring high wear resistance of these coatings remains an urgent task, especially when used under intense mechanical and thermal loads [5,6].

Most often Ni-based protective coatings are used to improve wear resistance. The nickel in the coating forms a dense and stable oxide layer, which provides high resistance to aggressive chemical media such as acids and alkalis and other [7]. Nickel-based protective coatings can be deposited by various methods, including electroplating, thermal spraying,

chemical vapour deposition, and PTAW (plasma transferred arc welding) [8–10]. This makes them available for use in a wide range of industries.

Thermal spraying techniques, including plasma spraying, detonation spraying, and high-velocity gas flame spraying (HVOF), can produce coatings with a variety of properties by using different materials and process parameters [11]. However, the structure of the resulting coatings is often characterised by porosity, oxide inclusions and microcracks, which can negatively affect their wear resistance [5,12].

To improve the adhesion strength and wear resistance of multicomponent coatings after gas-thermal spraying, various post-treatment methods are used. One of the promising approaches is the laser treatment of the coating surface [13–17]. Laser exposure allows local melting of the upper layers of the coating, contributing to the elimination of defects, reducing porosity, and improving adhesion between the coating particles and the substrate [18].

Studies [19] show that laser treatment can significantly improve the adhesion properties of coatings, hardness, and wear resistance. It was demonstrated in [20] that laser treatment of plasma ceramic coatings leads to an increase in adhesion strength by reducing porosity and forming a denser microstructure. The average tensile and compressive strength of CFRP (carbon-fibre reinforced polymer) with mesh structure ranges from 135% to 186% and from 127% to 199%, respectively, depending on the mesh structure applied, compared to the sandblasted treated control samples. Similar results were obtained in a study [21], in which laser treatment of HVOF-deposited carbide coatings improved adhesion strength and wear resistance.

Laser exposure leads to local melting and subsequent rapid crystallisation of the coating material, helping to reduce porosity, increase the density of the structure, and improve wear resistance [22]. The mechanism of improvement in adhesion strength and wear resistance by laser treatment is related to several factors. First, laser surface melting promotes the elimination of surface defects and the reduction in porosity, which reduces the number of potential fracture centres [23,24]. Second, laser treatment can cause changes in the phase composition and microstructure of the coating, contributing to the formation of stronger bonds between the coating particles and the substrate [25–27].

However, the efficiency of laser processing depends on a variety of parameters, including laser power, scanning speed, pulse duration, and properties of the coating itself [28,29]. Optimisation of these parameters is a key factor in improving the wear resistance of coatings without degrading other performance characteristics of the coating [30,31].

Due to the mass production of welding lasers, their price has decreased significantly, which in turn reduces the cost of post-processing technology of coatings [32]. Due to both transverse and longitudinal oscillations of different shapes (sinusoid, figure-eight, circle, triangle, rhombus, etc.), as well as by adjusting its magnitude, the shape of the remelted layer can be easily controlled [33]. Oscillation of the laser beam can increase the width of the remelted layer without greatly increasing its depth [34]. In this case, the efficiency and productivity of laser remelting are increased, and the cost of production is reduced. This mode is suitable for remelting an already-formed coating and avoids remelting the substrate together with the coating. Otherwise, the coating metal is diluted with iron, leading to a strong deterioration of the anticorrosion properties and, as a rule, to a decrease in hardness [35]. At the same time, at laser remelting of already formed coating, there is often a problem of cracks. It is especially relevant if the laser treatment process hardens the remelted metal 1.5 to 2 times.

The use of concentrated energy sources (such as laser beam, electron beam, etc.) in the formation of metal and metal-ceramic coatings allows for the high-performance creation of protective layers with controlled geometry and dense structure. Selection of filler

material and control of the penetration value during coating formation makes it possible to create coatings with specified properties for use in corrosive, abrasive and other external influences. This technology allows for the creation or modification of continuous and local coatings that have multifunctional properties and are resistant to electrochemical corrosion and abrasive wear. It has found wide application in the aerospace, energy, automotive and chemical industries. When forming this type of coating, one of the main existing problems is the occurrence of defects during the intensive process of thermal exposure and high rates of melting and solidification of the coating material. The occurrence of significant temperature gradients, thermal stresses and their concentration in the coating when using laser processing, thermal cycling of the coating material during the processing, phase transformations and the formation of brittle and fusible structures in the coating metal are the causes of the formation of hot and cold cracks in the coating [36].

There are various ways to solve the problem of cracking during laser processing:

- Control and limitation of the hard phase content and the use of additional alloying elements (e.g., rare earth oxides) allow for obtaining a more ductile and fine structure of the coating metal [36];
- Optimisation of the laser processing parameters and the use of numerical modelling to predict crack formation [36];
- Using preheating of the substrate before the formation of the coating allows for reducing the temperature gradient and thermal stresses in the coating metal [33];
- Using external action (e.g., ultrasonic vibrations or an electromagnetic field) during laser processing allows to reduce the grain size and residual stresses [36,37];
- Using post-thermal treatment of the formed coatings allows the creation of a uniform, fine and equiaxed structure of the coating metal [38].

When forming a NiCrMoFeCSiB coating using laser processing, the formation of hard phases (MeB or MeBC type) and low-melting eutectic phases (Ni-B, Ni-Si or Ni-B-Si systems) in the coating metal can be predicted. Therefore, the use of preheating is the most effective way to reduce temperature gradients and thermal stresses in the coating, which makes it possible to reduce the likelihood of cracks in the coating metal.

A study of laser processing, carried out earlier on thermally sprayed NiCrCoFeC-SiB/WC coatings using pulsed irradiation, showed a significant improvement in the wear resistance of coatings by up to 2.4 times [19]. However, thermal stresses induced by local heating resulted in coating cracks, especially in areas of passes overlapping. Moreover, when as-sprayed coatings are laser-processed, a strong metallurgical bond can be achieved only with a certain melting of the substrate, which leads to metal admixture and deterioration of properties. Coatings pre-treatment before laser processing by re-fuse in a furnace forms a low-porous and strongly bound layer. Furthermore, surface processing in “pass-by-pass” manner forms an undesirable “saw-shaped” profile. The implementation of an oscillated laser beam practically removed this issue, allowing for shallow flat-bottom molten pools, which are more convenient for surface technologies [33]. However, additional lateral movement of the molten pool due to transverse beam oscillation increases cooling rates and rather contributes to crack formation [33]. Thus, laser treatment of thermally sprayed coatings is an effective method to improve their performance, but cracking is a significant limitation of this approach. The reduction of temperature gradient by pre-heating parts remains one of the most effective ways to prevent cracks.

Another approach involving partial laser surface processing is realised in the present work, which suggests reducing the overall heat input due to a reduced portion of the surface being treated and retaining softer material portions that facilitate stress redistribution. A reduction in the effect of increasing wear resistance can be expected with a reduction in the portion of the surface being treated. An issue of the present study is to determine the

relationship between the amount of surface processed and the effect of improved wear resistance. A similar approach was applied in [39], where authors investigated thermally sprayed Ni-based coatings with 12.5% to 50% partially laser-processed surface. The authors indicated a linear dependence of wear on the amount of the processed surface under lubricated sliding conditions. The present study covers more severe conditions of dry abrasion wear and also includes a partial processing option in the range between 50% and 100% of the surface.

2. Materials and Methods

Self-fluxing Ni-based alloy powder (~67% Ni; 15.7% Cr; 4.69% Mo; 3.92% B; 4.11% Si; 2.72% Fe; 0.45% C; 1.94% Cu) was used as a spraying material to produce coatings for the experiments. Structural steel S235 (0.19% C; 1.5% Mn; 0.04% P; 0.040% S; 0.014% N; 0.60% Cu; Fe balance) plates of size 200 mm × 150 mm × 8 mm were used as a substrate. The coatings were deposited by oxyfuel flame spraying using Rototec 80 (Castolin Eutectic, Lausanne, Switzerland) spraying equipment and Motoman 100 (Yaskawa Nordic, Torsås, Sweden). The parameters of the spraying process were as follows: neutral flame; 230–250 °C substrate pre-heating temperature; 170 mm spraying distance; 250 mm/s spraying speed; 5 mm step between adjacent passes; 8 spray layers; grid-type spraying sequence. The average thickness of the deposited layer was 1.2–1.4 mm. Before spraying, the substrate surface to be covered was chemically degreased, grit-blasted, washed with isopropyl alcohol, and dried with a hot air stream. The sprayed layers were fused by heating in an electrical furnace at 1250 °C for 7 min. Before laser processing, coated samples were mechanically processed with a flat grinding machine to remove the slags formed and flatten the surface. The thickness of the coatings prepared for laser processing experiments was ~0.8–0.9 mm.

For laser processing, the FANUCI 4.0 PRO GenX (Fanuci, Gdansk, Poland) with laser beam wavelength $\lambda = 976$ nm was used. To obtain a wide and shallow molten pool with a flat bottom, which is more convenient for surface processing, a laser beam oscillation was applied. Based on the previous studies, a series of primary experiments were conducted applying 150 to 200 W laser power, 100 to 500 mm/min processing rate, and 2 to 3 mm oscillation amplitude, which formed molten pool depth between ~60% and 100%. Most of the obtained single laser paths were found to have cracks. To prevent crack formation, the experiments were repeated with the samples preheating at ~400 °C. The summary of the molten pools obtained under the conditions listed above is presented in Figure 1. The following parameters were chosen for the final experiment: laser power—175 W; processing rate—250 mm/min; preheating temperature—400 °C; oscillation mode—transverse; oscillation amplitude (the distance between positions of laser beam central axis at maximum transverse deflection)—2 mm; oscillation frequency—120 Hz. The conditions applied allowed uniform melting of the coating with stable and regular pool geometry, minimum surface ripples (Figure 2a), a path width of ~2.44 mm and a maximum molten pool depth of ~730 μ m, which is ~82%–85% from the coating thickness, avoiding substrate melting.

To obtain partial laser processing of the surface, parallel straight laser paths were produced with certain gaps between paths providing approximately 25:75, 50:50 and 75:25 (in %) of processed to unprocessed surface ratios (Figure 2b). Heat-treated coating in a furnace and coating with fully laser-processed surface coating were used as a reference. The entire coating laser processing was conducted applying ~30% path overlapping.

The microstructure of furnace fused and laser-processed coatings was characterised using scanning electron microscope SEM JEOL JSM-7600F (JEOL, Akishima, Japan) equipped with an energy dispersive spectrometer (EDS) Inca Energy 350 SDD X-Max 20 mm² (Oxford Instruments, Oxford, UK) for X-ray microanalysis. Polished and etched cross sections were

examined. $\text{HNO}_3:\text{CH}_3\text{COOH} = 1:1$ etchant was used. The analysis was performed under 10 kV acceleration voltage.

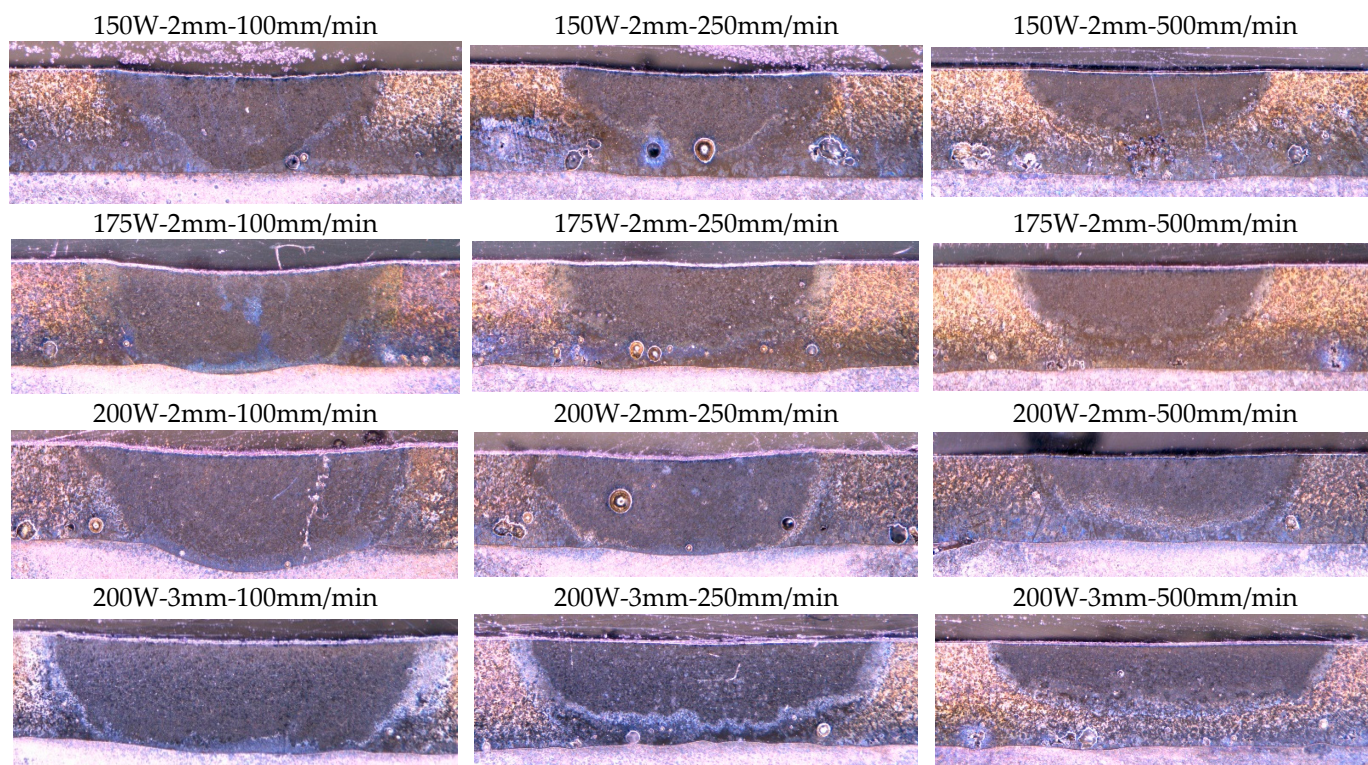


Figure 1. Molten pools obtained at different laser processing parameters and preheating at 400 °C.

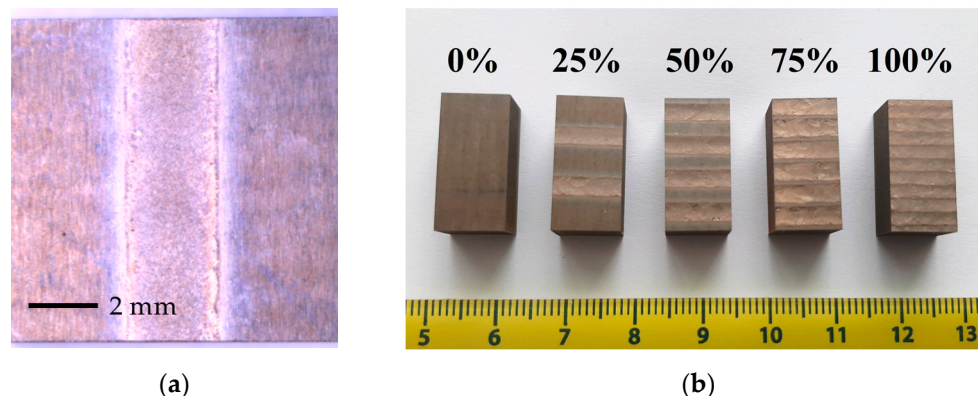


Figure 2. Stereo microscope image of a single laser-processed path obtained with 175 W laser power, 250 mm/min processing rate, 2 mm amplitude transverse oscillation and ~400 °C pre-heating temperature (a); general view of the furnace-treated sample (0%) and samples with 25%, 50%, 75%, and 100% of laser-processed surface (b).

The phase composition of the coatings was analysed by means of X-ray diffractometer SmartLab (Rigaku, Wrocław, Poland) equipped with an X-ray tube with a 9 kW rotating Cu anode. The measurements were made using Bragg–Brentano geometry with a graphite monochromator on the diffracted beam and a step scan mode with a step size of 0.02° (in 2θ scale) and a counting time of 1 s per step.

The microhardness of the coatings was measured using Zwick Roell ZHμ (ZwickRoell GmbH & Co. KG, Ulm, Germany). Measurements were carried out using the Vickers method with a 200 g load and a 15 s duration on the polished cross sections. To evaluate the microhardness distribution in the horizontal direction, measurements were conducted

along the coating surface at $\sim 150\ \mu\text{m}$ depth from the surface applying a $150\ \mu\text{m}$ indentation step. The depth microhardness profile was obtained from measurements made in the centre of the molten pool with a $100\ \mu\text{m}$ indentation step in depth.

For the tribological characterisation of coatings, Microtest tribometer was used. “Ball-on-disc” dry sliding tests were conducted. Before the coating test, the surface was pre-polished to $R_a \sim 0.46\ \mu\text{m}$ (measured with the profilometer TR-200 with an accuracy $\pm 0.01\ \mu\text{m}$). The test parameters were as follows: sliding distance—300 m; sliding speed—100 rpm; radius—2.0 mm; load—10 N; temperature— $22 \pm 1\ ^\circ\text{C}$; indenter—6 mm diameter ball made of tempered stainless steel AISI52100. The wear resistance of the coatings was evaluated by mass loss. The analytical balance Vesi Radwag AS/220.R2 with an accuracy of 0.00001 g was used to measure the mass of the samples before and after the tribology test. Before weighing, the test samples were cleaned in an ultrasonic bath for 10 min. The resistance to wear of the coating was calculated by dividing the sliding distance by the mass loss and was expressed in $\text{m}/\mu\text{g}$. The average values of three tests are presented in the paper. The friction coefficients were calculated after the test data for the first 30 m of the sliding distance were eliminated; the average values are presented in the paper with standard deviation.

The effectiveness of the partial laser processing method was evaluated through the dry two-body abrasive wear resistance test using a 2101TP machine (Tochpribor, Ivanovo, Russia) at 35 N load and SiC grinding paper #220 (grit size of $\sim 58\ \mu\text{m}$) as a counter-abrasive. First, each sample was ground for a sliding distance of 350 m to eliminate roughness effects. Then, each sample was tested during a 3400 m sliding distance. The abrasive paper was renewed, and the samples were weighted every 350 m. The Vesi Radwag AS/220.R2 balance with a precision of 0.00001 g was used.

3. Results

3.1. Characterisation of Coatings Obtained by Heating in Furnace and Laser Processing

The strategy of partial laser surface processing suggests the formation of the periodic structure consisting of portions of initial material (in this case—deposited and furnace-treated coating) and material (coating) modified by laser processing, which properties and volume ratio will predetermine the overall performance of the coating. The structural and tribological characterisation of the initial coating material and laser-processed coating material, both constituting a partially laser-processed coating, is given below.

3.1.1. Coatings Microstructure and Phase Composition

The typical coating microstructure obtained after heat treatment in a furnace is shown in Figure 3a,c. There were three major structural constituents observed: a γ -Ni matrix (pt. 1 and 2, Figure 3c and Table 1)—a solid Ni-based solution containing $\sim 6.3\%$ of Fe, $\sim 5.65\%$ of Cr, $\sim 3.17\%$ of Si and $\sim 3.4\%$ of Cu; a Ni-based phase located between the dendrites of γ -Ni phase and besides Cr, Fe and Cu containing also some boron, which allows identifying this phase as a Ni-B eutectic (pt. 5 and 6, Figure 3c, Table 1); precipitation phase consisting mainly of Cr and also B and containing C and Mo (pt. 3 and 4, Figure 3c, Table 1).

The laser-processed coating was found to be composed mainly of the γ -Ni, eutectic and hard precipitation phase, also (Figure 3b,d). However, the microstructure appearance changed, and the EDS analysis revealed some redistribution of the elements in the major phases. Thus, a greater concentration of alloying elements can be pointed out in a γ -Ni solid solution. The eutectic phase contains a significant amount of Fe and Si, which in the furnace-treated coating were concentrated mainly in a solid solution phase. The precipitation phase contains slightly less carbon and is richer in Mo, Fe and Ni. Moreover, the coating microstructure after laser processing looked to be more uniform, refined and

containing a more eutectic phase. As is well known, there is a strong relationship between the microstructure fineness and material hardness, which, according to Hall–Petch’s relationship [40], increases with reducing grain size. In laser-processed materials, this effect is associated with high heating-cooling rates typical for concentrated laser treatment. To reduce crack formation, samples were preheated, resulting in a drastically reduced temperature gradient and partially diminished quenching effect. However, even under such conditions, laser processing formed a more uniform and refined structure, which allows expecting a hardness increase and wear resistance improvement.

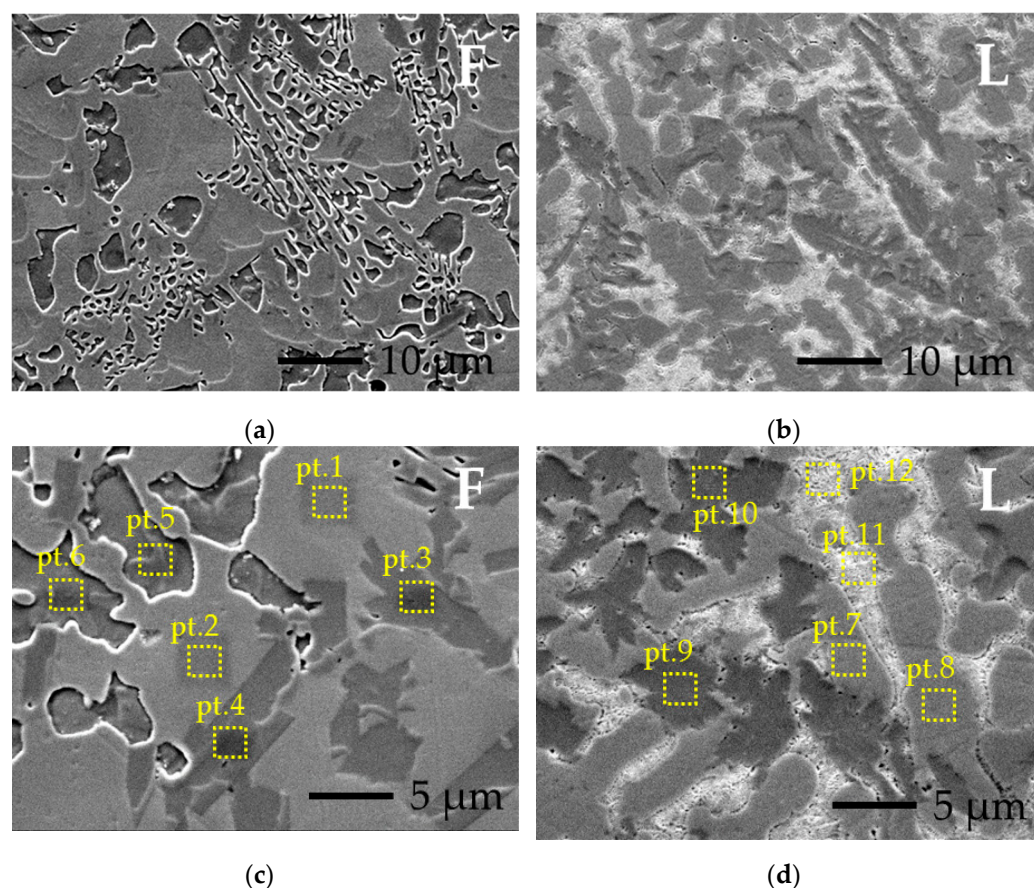


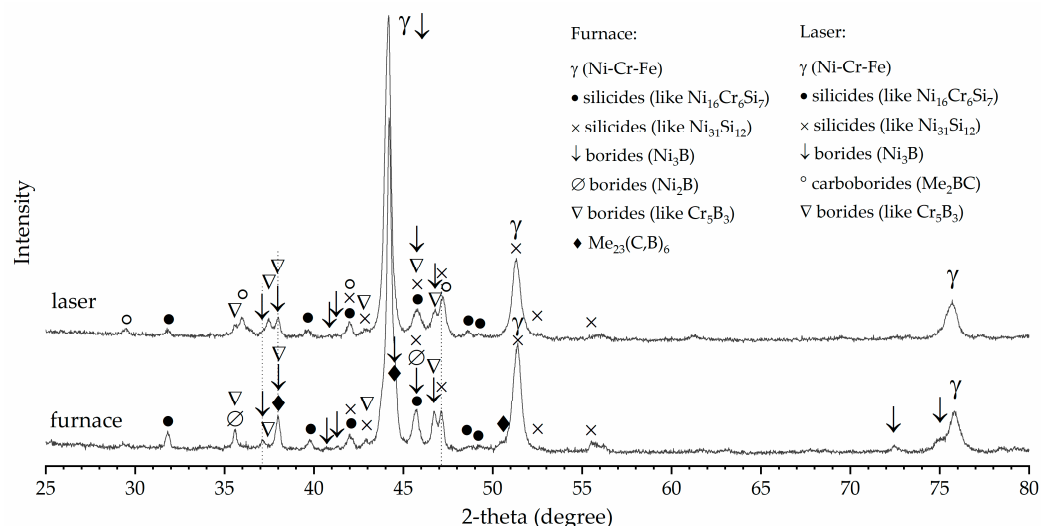
Figure 3. Microstructure of coatings with marked points of EDS analysis: (a,c) coating heated in furnace (F); (b,d) laser-processed coating (L); SEM, $\times 2$ k (a,b) $\times 4$ k (c,d) magnification applied.

XRD patterns of the coatings studied are presented in Figure 4. For both samples, the most intense reflections at 2-theta angle $\sim 44.15^\circ$, $\sim 51.42^\circ$, and $\sim 75.68^\circ$ are attributable to an *fcc* Ni-Cr-Fe phase with a parameter $a \approx 3.554$ and with a slight shift of the major reflection ($\sim 44.15^\circ$) to a higher d spacing for laser-processed sample, which agree well with microstructural analysis and EDS and can be associated with a higher concentration of alloying elements in a nickel-based γ -phase after laser processing. The presence of alloying elements in a solid solution provides a hardening effect, mainly associated with the distortion of atomic lattice and inhibition of dislocation movement due to this [41]. The higher concentration of Cr, Mo and Fe (each has atomic radii greater than Ni) in γ -Ni allows expecting a stronger hardening effect and, accordingly, contributes to a wear resistance improvement.

Table 1. Elemental composition in points shown in Figure 2 (by EDS, in wt.%).

Point	Ni	Cr	Mo	Fe	Cu	Si	¹ B	¹ C	The Phase Estimated
Furnace-treated coating									
pt. 1	81.19	5.66	0.32	6.26	3.39	3.16	-	-	Ni-base solid solution
pt. 2	81.49	5.54	-	6.29	3.41	3.18	-	-	
pt. 3	1.65	60.16	11.12	-	-	-	19.40	7.67	Borides/ Borocarbides
pt. 4	0.37	63.80	9.96	-	-	-	20.40	5.48	
pt. 5	83.86	9.72	0.56	4.06	1.79	-	+	+	Eutectic
pt. 6	90.29	7.37	0.55	1.51	0.28	-	+	+	
Laser-processed coating									
pt. 7	67.06	10.54	1.99	15.23	3.31	1.88	-	-	Ni-base solid solution
pt. 8	69.10	9.07	1.13	15.56	3.03	2.11	-	-	
pt. 9	2.81	48.51	14.24	6.68	0.21	0.09	20.91	6.54	Borides/ Borocarbides
pt. 10	2.88	48.33	15.62	6.08	0.30	0.11	19.51	7.19	
pt. 11	76.34	5.97	0.98	10.49	2.81	3.40	+	+	Eutectic
pt. 12	78.59	4.58	-	10.50	2.83	3.51	+	+	

¹ “+” shows that the element presents in an analysed phase in a few amount, but it was removed from the composition to avoid too much distortion of the results.

**Figure 4.** XRD patterns of coatings heat-treated in a furnace and processed with a laser.

The identification of minor reflections (in both patterns) was complicated because of the low intensity of peaks and the absence or overlap of some peaks. With high probability, both samples contain silicides; the part of peaks is well fitted to those such as $\text{Ni}_{31}\text{Si}_{12}$ and $\text{Ni}_{16}\text{Cr}_6\text{Si}_7$. Taking into account the EDS results (Table 2), it could be assumed that in a furnace-treated coating, silicides are present in the solid solution phase in the form of dispersive inclusions. Furthermore, this coating can contain nickel borides both Ni_2B and Ni_3B , which frequently compose a eutectic phase in such type coatings, while a hardening phase observed in Figure 3c (pt. 3,4) to be highly likely is of type Cr_5B_3 , in which Cr is partially replaced by Mo and B is partially replaced by C. Furthermore, the presence of other types of precipitation (like $\text{Me}_{23}(\text{C,B})_6$) can be assumed from the XRD pattern.

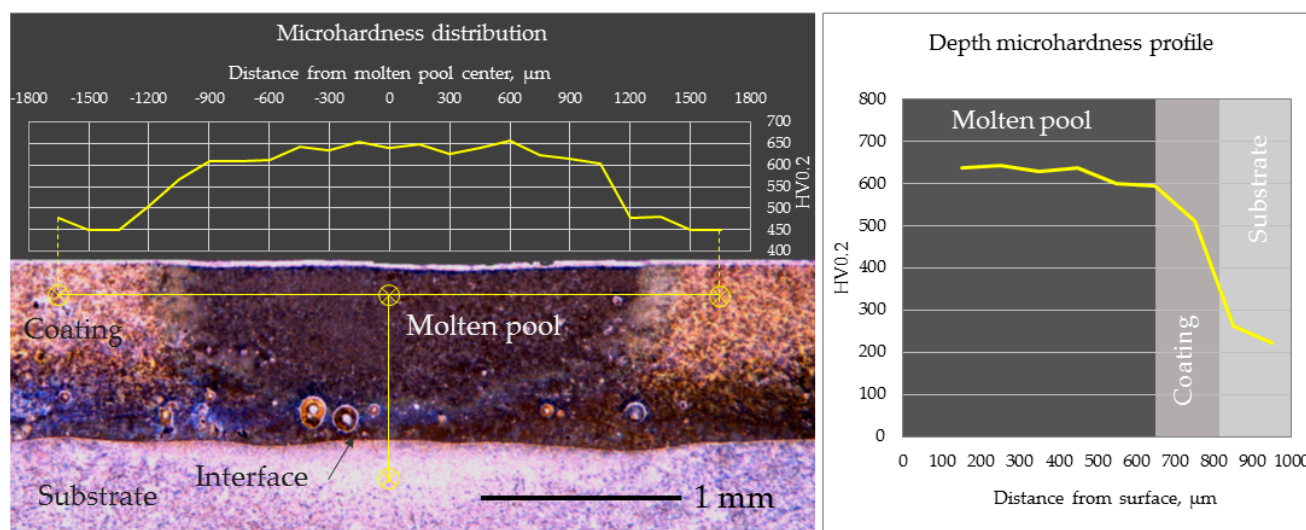
Table 2. Tribological characteristics of coatings heat treated in a furnace and processed with a laser.

Sample	Sample Mass Loss, mg	Counter-Body Mass Loss, mg	Coefficient of Friction (30–300 m)	Wear Resistance, m/μg
Furnace	0.533 ± 0.050	0.040 ± 0.006	0.550 ± 0.052	0.563
Laser	0.267 ± 0.060	0.100 ± 0.008	0.380 ± 0.026	1.124

The reflections in the XRD pattern of the laser-processed coating also indicated a high probability of the presence of Cr_5B_3 , which agrees well with the EDS results. Furthermore, some reflections can be attributed to Me_2BC , which can be part of the complex eutectic phase. The possible formation of higher borocarbides under laser processing may be associated with a higher processing temperature and a more uniform distribution of elements as a result of additional stirring of the melt. A strong covalent bond skeleton formed by boron provides high hardness of borides and borocarbides [42]. With an increase in boron concentration in higher compounds, the covalent bonding prevails providing higher hardness and melting point [43]. Thus, the increase in coating hardness and wear resistance can be expected with the formation of higher borocarbides.

3.1.2. Microhardness and Tribology of Coatings

The average microhardness of the coating after heat treatment in a furnace was 478 ± 20 HV0.2. After laser processing without sample preheating, the microhardness of coatings was increased to 713 ± 19 HV0.2, i.e., by 1.49 time, which is largely due to high heating-cooling rates providing a visible microstructure refinement effect. However, all of the processing regimes applied resulted in crack formation. Samples preheating reduced the temperature gradient, thus preventing the cracks. However, it also resulted in a coarser microstructure, partially diminishing the hardening effect. However, the average hardness of laser-processed preheated coating in a main zone (~ 150 μm from the surface) was 631 ± 16 HV0.2, which is 1.32 times higher compared to that of the furnace-treated coating. As the results of the EDS and phase analysis showed, the hardening effect was also due to the higher saturation of γ -Ni solid solution and the formation of higher borides/carboborides. Furthermore, the measurements showed a uniform and stable microhardness distribution in a laser-processed zone both along the surface and in-depth (Figure 5).

**Figure 5.** Stereo microscope image of laser-formed molten pool with a schema of microhardness measurements and microhardness distribution profiles along the surface and in-depth.

The statistical hypothesis $H_0 : \mu_i = \mu_j$ against the alternative $H_1 : \mu_i > \mu_j$, where $i \in \{A, B\}$, and $j = C$, were used to test the significances in the differences of the means μ_i and μ_j of the microhardness of the specimens of the different treatments by using two-sample unequal variance one-tailed distribution t -test when the significance level $\alpha = 0.05$. The performed test has shown that the null hypotheses H_0 should be rejected and the alternatives $H_1 : \mu_A > \mu_C$, p -value $p = 2.67 \cdot 10^{-26}$ as well as $H_1 : \mu_B > \mu_C$, $p = 3.94 \cdot 10^{-21}$, should be accepted as $\alpha = 0.05$. Therefore, the differences in the means of the microhardnesses of the specimens A (microhardness of coatings processed by laser without preheating) and C (microhardness of coatings after heat-treatment in a furnace), and B (microhardness of coatings processed by laser with preheating) and C (microhardness of coatings after heat-treatment in a furnace) are statistically significant.

During the tribological test, the counter-body (steel ball) rubs the test surface along the circumferential path. At any moment of the test, a ball is in local contact with the surface, which does not allow for evaluating overall resistance of the coating consisting of laser-processed and unprocessed portions. Therefore, a tribological study was conducted only for two types of coatings: furnace-treated and 100% laser-processed, excluding partially processed samples, making it possible to assess the effect of laser processing on the tribological properties of the tested coating and giving tribological characteristics of the materials, which compose the partially processed coating. The results revealed (Table 2) that under dry friction conditions ‘metal-to-metal’, more uniform and refined microstructure and changes in phase composition obtained with additional laser processing of the coating, provided a reduction in friction coefficient by 31% and 2 times higher wear resistance (assessed by sample mass loss), once again confirming overall effectiveness of laser processing method even at the moderate hardness increase.

Analysis of the studied surfaces after dry sliding tests revealed more significant wear traces on the furnace-heated samples compared to laser-processed (Figure 6a,b), which is in a good agreement with mass losses. Both samples exhibit a similar worn surface appearance (Figure 6c,d), indicating a substantially similar wear mechanism. A lot of wear debris adhered and a smooth surface of wear track in the absence of scratches suggest mainly deformative-adhesive wear. However, laser-processed sample exhibited also signs such as cracks and delamination, indicating a partial transition to a delamination wear mechanism of coating due to increased hardness after laser processing. Nevertheless, the overall resistance of laser-processed surface was even improved, while higher friction coefficient and prevalence of deformative-adhesive wear mechanism for less hard furnace-heated coating resulted in a lower wear resistance.

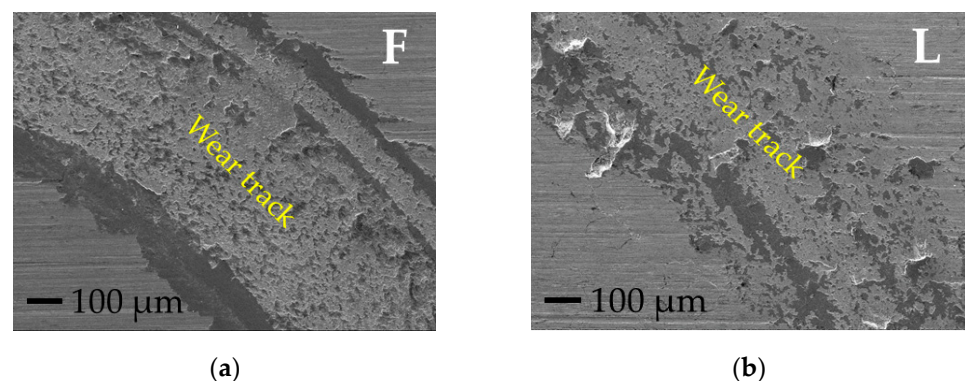


Figure 6. Cont.

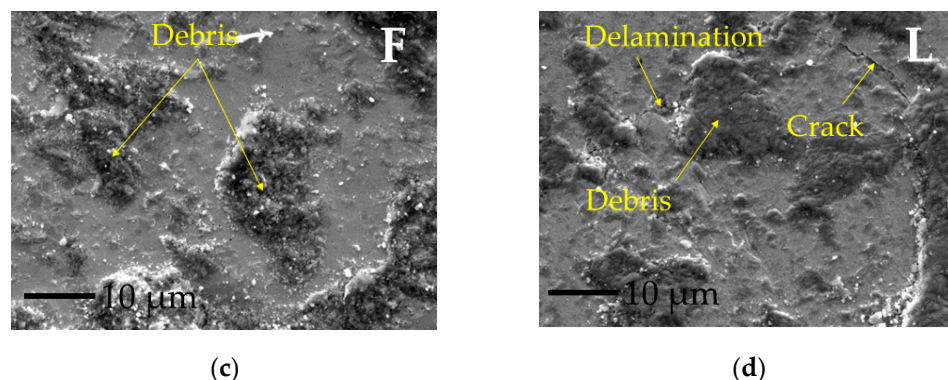


Figure 6. SEM micrographs of wear tracks for furnace-heated sample (a,c) and for laser-processed sample (b,d): (a,b) overall view of wear tracks under $\times 100$ magnification; (c,d) enlarged view of wear tracks under $\times 2\text{ k}$ magnification.

3.2. Wear Resistance Study of Coatings

To evaluate the effectiveness of the partial coating surface laser processing, samples with 25%, 50%, and 75% portion of the laser-processed surface were tested under two-body dry abrasive wear conditions under 35 N load for 3400 m distance and compared with the furnace-treated and fully laser-processed coatings. The curves of the mass loss accumulation of samples during the wear test are presented in Figure 7, showing a nearly linear wear character for all groups tested. As expected, the mass losses were less for laser-processed samples and the wear resistance was improved with an increase in the portion of the laser-processed surface. However, differently from results reported in [39], the improvement effect was not found to depend linearly on the surface area processed. This can be seen more clearly in Figure 8: for example, the difference in mass losses at a 75% and 100% processed surface is insignificant.

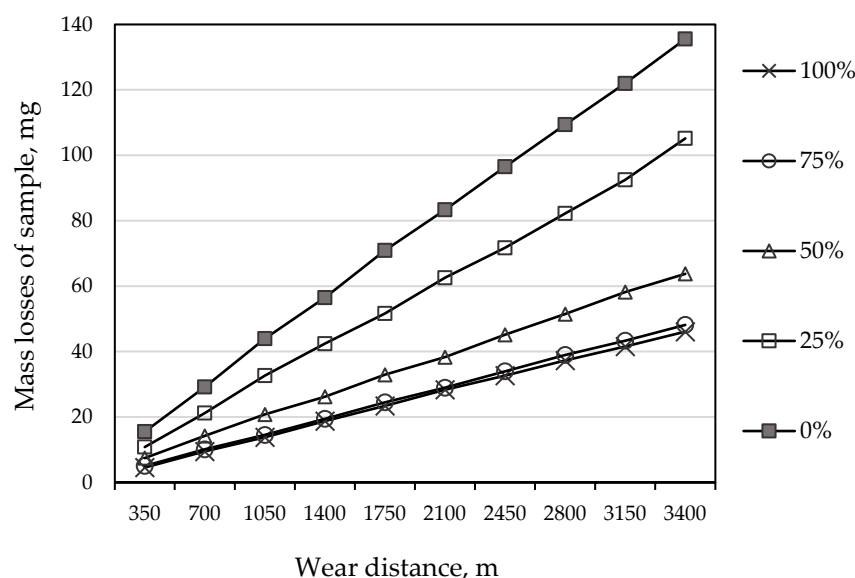


Figure 7. Two-body dry abrasive wear curves for tested samples with different amounts of the laser-processed surface.

The wear resistance (WR) of the coating, calculated as a total wear distance (3400 m) divided by the total mass loss, was found to increase by 2.94 time after full laser-processing (Table 3). Using the WR values presented in Table 3, the improvement in WR per 1% of processed surface can be calculated: $(WR_{100\%} - WR_{0\%})/100\% = (73.785 - 25.079)/100\% = 0.487\text{ m/mg per }1\%$. Respectively, the expected wear resistance ($WR_{exp.}$) can be calculated

for coatings laser-processed to a different extent. As the results presented in Table 3 show, in the case of a 25% processed surface, the experimentally assessed WR value was 13.2% less than the expected value, indicating that the resistance of the coating in this case is mainly predetermined by the properties of the untreated part. When increasing the portion of the processed surface by up to 50%, the experimentally received WR was 7.9% higher than the expected one. At 75%—experimental WR exceeded the expected one by 14.6% and differed from the fully processed sample only by 4.3%.

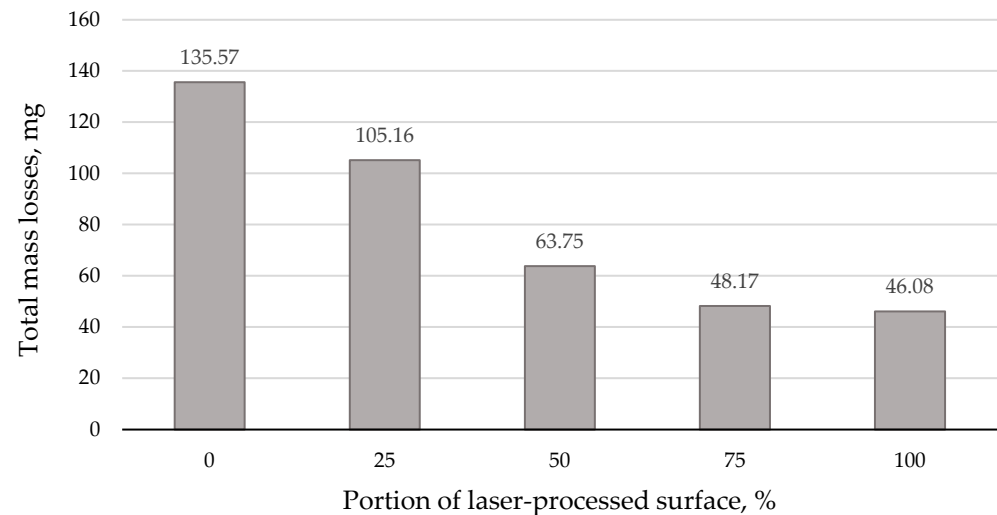


Figure 8. Total mass losses for tested samples with different amounts of the laser-processed surface after two-body dry abrasive wear for a 3400 m distance.

Table 3. Wear resistance characteristics of tested coatings.

Parameter	Portion of Laser-Processed Surface				
	0%	25%	50%	75%	100%
Total mass loss ML, mg	135.57	105.16	63.75	48.17	46.08
Wear distance D, m	3400	3400	3400	3400	3400
Wear resistance WR = D/ML, m/mg	25.079	32.332	53.333	70.583	73.785
Expected wear resistance WR _{exp} , m/mg	-	37.256	49.432	61.608	-
Difference, m/mg (WR – WR _{exp})	-	−4.924	+3.901	+8.975	-
Difference, % 100 × (WR – WR _{ex})/WR _{ex}	-	−13.2	+7.9	+14.6	-

4. Conclusions

In the present paper, the effectiveness of the partial laser processing of wear resistance coatings was studied. Thermally sprayed NiCrMoFeCSiB coatings were used for the experiments and a fibre laser with laser beam wavelength $\lambda = 976$ nm was applied for the coating surface processing. The processing parameters, which provide sufficient melting of the coating with a molten pool depth between ~60% and 100%, are found to create thermal cracks. The preheating of the samples prevented the formation of cracks, but at the same time reduced the hardening effect.

The results of the study revealed that even at the drastically reduced temperature gradient, laser processing forms a denser and more uniform refined structure with more saturated solid solution phase and higher strengthening phases, which can be associated with high processing temperature and more uniform distribution of elements in a melt. This

results in greater hardness and significantly improved resistance to friction and abrasive wear: a ~30% increase in hardness provided a ~2 times higher resistance to friction and ~2.9 times higher resistance to abrasive wear.

Studies of the abrasive wear of NiCrMoFeCSiB coatings have shown that even partial laser treatment of the surface allows the achievement of significant improvement in coating performance. The laser processing of less than 50% of the surface is less effective: in this case, it can be expected that the wear resistance of the surface will be predetermined by the properties of the less hard untreated part to a greater extent than the area of this surface. However, if the area of the hardened surface reaches 50% or more, the wear resistance of the surface will be predetermined by the hard part and to a greater extent than calculated by the proportionally occupied part of the surface, making this method effective for improving wear resistance. This allows only a portion of the surface to be laser processed, leaving islands of more ductile material capable of redistributing thermal stresses and reducing the risk of cracking, while providing only a minor loss in wear resistance, also making the process cheaper and faster. It can be expected as well that additional optimisation of the laser processing parameters, preheating temperature, and laser-patterning strategy could contribute to the even higher effectiveness of the method.

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Abbreviations

The following abbreviations are used in this manuscript:

XRD	X-ray diffraction
EDS	Energy dispersive spectrometry
WR	Wear resistance

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