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Laser surface remelting of powder metallurgy high-speed steel

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Abstract. The effect of laser processing on the structure, microstructure and hardness of high-speed steel produced by powder metallurgy was investigated. The samples were surfaces remelted with impulse CO_2 laser radiation under different operation conditions. In the remelted layer, the presence of full remelting, partial remelting and heat affected zones was detected. As a result of concentrated laser beam treatment, microstructures characteristic of the rapid crystallization process were observed. The microstructure in the full remelting zone was characterized by a fine microdendritic structure with the average distance between the secondary axes of dendrites below 1 μm and the dissolution of primary carbides. Retained austenite was found in the remelted samples, the amounts of which depended on the treatment parameters and grew with an increase in the speed of the laser beam movement. There was no unequivocal effect of the distance of the irradiated surface from the focus of the beam focusing system on the content of retained austenite. Due to the presence of retained austenite in the remelted part, the hardness decreased by about 23% compared to the hardness of the material before the treatment. On the other hand, laser processing leads to strong refinement of the microstructure and eliminates the residual porosity of powder steels, which can increase the toughness and cutting performance of steel. The research also showed the possibility of shaping the geometry of the remelting zone by the appropriate selection of machining parameters.

Key words: laser remelting treatment, CO_2 laser, P/M high-speed steel, surface modification.

1. Introduction

High-speed steels (HSS) produced by powder metallurgy (P/M) are increasingly competing with steels produced in a traditional way. The advantage over their classic counterparts results from the more homogeneous microstructure, lack of segregation and banding of carbides as well as greater grain refinement [1, 2]. Compared with conventional cast or wrought parts, high-speed steel fabricated using powder metallurgy technology exhibits improved wear resistance, hardness, heat resistance and toughness [3]. The manufacturing of products by the powder metallurgy method is also characterized by a lower temperature of the manufacturing operation and more effective use of the starting material. All this makes steel made by powder metallurgy an unrivaled material in many aspects. However, the PM process is relatively complicated and generates high costs associated with powdering and hot isostatic pressing [4, 5]. The microstructure and properties of sintered high-speed steels are shaped primarily during the manufacturing process by optimizing individual technological operations and process parameters. The sintered steel microstructure can also be shaped by additional surface treatment which the material undergoes after or before the final heat treatment. One of the solutions increasingly used in shaping the microstructure of the surface layers of engineering materials is surface remelting carried out using concentrated heat sources [6–13]. The use of a laser beam, plasma arc or electric arc leads to the formation of a surface layer with completely new properties, which are the result of very fast melting of the material and rapid crystallization. In the case of the materials produced by the powder metallurgy method, remelting carried out with concentrated heat sources also allows for the reduction of residual sintering porosity, whose presence results from the specificity of forming the material by the powder metallurgy method. Due to the residual porosity, some properties such as toughness, fatigue and wear resistance are often lower than those of the material processed by conventional routes [2]. The surface treatment of high-speed steels is most often carried out using laser technologies. The choice of laser technologies is dictated primarily by the ease of computer automation and control as well as the short process time. Laser surface melting does not involve change in the overall chemical compositions and no additional precious materials are required [13]. Also, it is worth noting that there is a possibility of precisely focusing the beam on a selected surface and achieving huge temperature gradients in the material, which affects the solidification rate of the melted material. Considering the nature of high-speed steels and the specificity of the effect of laser heat on the material being processed, the use of laser technology in modifying the surface of high-speed steel seems to be a promising solution [14]. As the literature data indicate, the attention of research teams focuses mainly on the surface remelting of high-speed steels produced in a conventional manner [14–20]. For instance, in paper [14] Chaus et al. analyzed the effect of time and energy parameters of the pulsed laser treatment on the structure formation and hardness of the R6M5-type HSS upon surface melting after full heat treatment. They found that the laser-induced remelting causes a significant refinement of both the dendritic structure of the solid solution and of the carbide constituent of high-speed steel. As a result of surface remelting, the hardness of high-speed steel decreased. The hardness changed in a wide range and did not exceed the hardness of the heat-treated base material. In turn, J. Arias et al. [20] analyzed the microstructure of Nd:YAG continuous wave laser-melted surface of AISI M2 high-speed

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steel. They found a dendritic structure in the melted zone and a heterogeneous cellular structure in the partially melted zone. M_2C carbides with different morphologies were identified in the resolidified surface layer after laser-melting. The surface layer obtained after laser-melting of the surface was homogeneous and highly refined, with no cracks, discontinuities, or porosity.

From the literature data it can be seen that there are decidedly fewer works on the surface remelting of steels produced by powder metallurgy [2, 21–26], including very few studies on high-speed steels [2, 23–26]. For example, the authors of [25] subjected two high-speed steels, ASP23 and ASP30 formed by powder metallurgy, to surface remelting. The machining was carried out using a 2.5-kW Nd:YAG laser. It was found that the laser-melted zone of the HSSs consisted of fine dendrites of austenite crossed by an extremely fine carbide precipitation network or the eutectic without primary large carbides and with high chemical homogeneity. Compared to the annealed and conventionally hardened HSS, the corrosion resistance of laser-melted HSS was found to be improved, as evidenced by a shift in the corrosion potentials in the noble direction and a reduction in the corrosion current densities by 5.5 times. In turn, Jurci et al. [21] subjected PM ledeburite steel Vanadis 6 to laser remelting. The surface treatment was carried out using an Nd:YAG laser with an irradiation wavelength of 1064 nm, operating in a continuous regime. The steel was subjected to standard heat treatment, i.e. quenching and tempering before surface remelting. They found that the microstructure consisted of the matrix and two morphological types of carbides, namely M_7C_3 and MC types. The matrix was mostly austenitic, but the presence of a portion of martensitic needles was also evident. They also found that laser surface melting and subsequent rapid solidifying led to softening of the material, due to the presence of retained austenite.

Surface remelting of sintered high-speed steels is an issue with a high cognitive and application potential, which is unfortunately relatively poorly documented in the world literature. This fact prompted the author of this work to carry out his own research in this area. The assessment of the possibilities of using surface remelting in shaping the microstructure of sintered high-speed steels is the subject and the main aim of the research work.

2. Materials and experiment procedures

2.1. Materials. The test material consisted of cuboidal samples with dimensions of 60×30×9 mm made of commercial sintered high-speed steel, whose chemical composition is given in Table 1. The steel used in the work is intended for heavily loaded tools, both for machining and for plastic working. This steel is particularly recommended, e.g. for machining metals based on nickel and titanium, and for all types of tools that require very high compressive strength. Before laser melting, the specimens were subjected to standard heat treatment, i.e. quenching and then tempering three times (Table 2). The austenitization temperature was ≈ 1180°C. The treatment was carried out in a vacuum oven.

Table 1
Chemical composition of P/M HSS

Content of elements [wt%]					
W	***Co***	***V***	***Cr***	***Mo***	***C***
10.14	7.75	4.73	4.64	1.87	1.66
Si	***Mn***	***Ni***	***P***	***S***	***Fe***
0.56	0.29	0.16	0.02	0.017	rest

Table 2
Heat treatment process of P/M HSS

Heat treatment		Temperature / Time
Quenching	Heating I	550°C / 900 s
	Heating II	850°C / 900 s
	Austenitizing	1180°C / 150 s
Tempering		3×560°C for 7200 s

2.2. Laser processing. Surface remelting treatment was performed using a CO_2 laser with impulse work characteristics generating a laser beam of TEM_{00} mode. No coatings were applied to enhance the absorption of laser radiation. The laser power was 1200 W, pulse duration 45 ms, and pulse interval 40 ms. The distance of the irradiated surface from the focus of the beam focusing system Δl was from 28 mm to 48 mm, and focal length f was 250 mm. Laser head speed V was 750 mm/min, 800 mm/min and 850 mm/min. The processing parameters as well as the bandwidth and depth of microstructural changes are presented in Table 3. The measurement of the microstruc-

Table 3
Surface treatment parameters and dimensions of modified zone

No.	Laser head speed V [mm/min]	Distance of irradiated surface from focus of beam focusing system Δl [mm]	Bandwidth [mm]	Depth of microstructural changes [mm]
1	750	28	3.20 ± 0.1	4.81 ± 0.1
		32	3.18 ± 0.1	4.12 ± 0.1
		36	1.66 ± 0.1	1.07 ± 0.05
		40	1.86 ± 0.1	0.97 ± 0.05
		44	2.08 ± 0.1	0.93 ± 0.05
		48	2.32 ± 0.1	0.83 ± 0.05
2	800	28	2.90 ± 0.1	4.65 ± 0.1
		32	2.96 ± 0.1	3.84 ± 0.1
		36	1.55 ± 0.1	0.89 ± 0.05
		40	1.71 ± 0.1	0.87 ± 0.05
		44	1.99 ± 0.1	0.87 ± 0.05
		48	2.27 ± 0.1	0.81 ± 0.05
3	850	28	2.17 ± 0.1	4.60 ± 0.1
		32	2.06 ± 0.1	3.14 ± 0.1
		36	1.50 ± 0.1	0.87 ± 0.05
		40	1.65 ± 0.1	0.85 ± 0.05
		44	1.92 ± 0.1	0.80 ± 0.05
		48	2.21 ± 0.1	0.78 ± 0.05

tural changes zone was made on the etched cross-sections. The effects of remelting were evaluated based on macro- and microscopic examinations, X-ray structural studies, and hardness measurement. The microstructure tests were carried out using an Olympus GX41 light microscope and a JOEL JSM-6610LV scanning electron microscope. The specimens for microstructural investigations were polished and etched to reveal the grain boundary. A fracture for fractographic research was obtained by breaking a sample using Charpy hammer. The sample was previously cut on the side opposite the modified surface, and the cut depth was about 5 mm. The macroscopic analysis was carried out using an Olympus SZ61 stereoscopic microscope. X-ray phase composition tests were carried out using a Seifert XRD-3003 X-ray diffractometer, with cobalt lamp radiation $\lambda_{CoK\alpha 1} = 0.17902$ nm. The angular step was 0.05° and the pulse counting time was 6 s. The hardness was measured using a Shimadzu HMV-G20 microhardness tester equipped with a Vickers penetrator. A load of 1961.4 mN and a load time of 10 s were used.

3. Results and discussion

3.1. Macroscopic investigations. An important aspect of the work was to assess the possibilities of shaping the dimensions of the zone of microstructural changes by appropriate selection of treatment parameters. Analysis of the nature and size of the changes in the material microstructure as a function of the laser processing parameters showed several relationships. Namely, it was found that by reducing Δl, i.e. the distance of the irradiated surface from the focus of the beam focusing system, an increase in the depth of structural changes is obtained in all samples, but only in some samples there is a simultaneous reduction in the bandwidth (in this case the bandwidth is understood as the remelting diameter in the place of laser beam interaction). In the case of bands obtained at the smallest Δl values, i.e. equal to 28 and 32 mm, the bands had a very irregular and variable shape, as a result of which the remelting width varied depending on the place of measurement and no rational relationship was found in this case. This condition should be explained by an extremely dynamic course of the remelting process as well as the crystallization of the material itself, which was accompanied by the least favorable changes in the geometric structure of the surface of all the remelted samples. During the research it was found that the bandwidth and remelting depth decrease with increasing the speed of the laser head. Apart from the bands obtained at Δl = 28 mm and 32 mm, the largest remelting width of approximately 2.32 mm was obtained after applying Δl = 48 mm and V = 750 mm/min, and the smallest width of approximately 1.50 mm in the case of the remelted band using Δl = 36 mm and V = 850 mm/min. On the other hand, the largest penetration depth of approximately 1.07 mm was obtained for the sample melted using Δl = 36 mm and V = 750 mm/min, and the smallest penetration depth of approximately 0.78 mm was obtained after using Δl = 48 mm and V = 850 mm/min. The width and depth of the bands were measured on transverse metallographic specimens. Extremely high heating and cooling speeds occurring during remelting increase the risk of cohesion loss in the solidifying material. This risk in the case of a material produced by powder metallurgy may be increased by the pores present in the material, which may cause uneven heat flow from the remelting zone. Therefore, when assessing machining efficiency, particular attention was paid to the presence of this type of structural defects in the laser beam interaction zone.

Microcracks were found only in the case of the remelted samples using Δl = 28 mm and Δl = 32 mm and, as can be seen in Fig. 1, in most cases they were on the edge of the band or slightly touched the remelting zone. For the remaining samples, no cracks, discontinuities, or porosity were found. Examples of the macroscopic effects of the remelting samples are shown in Fig. 1. Figure 2 shows cross sections of the laser-treated bands. The width and depth of the microstructural changes were measured.

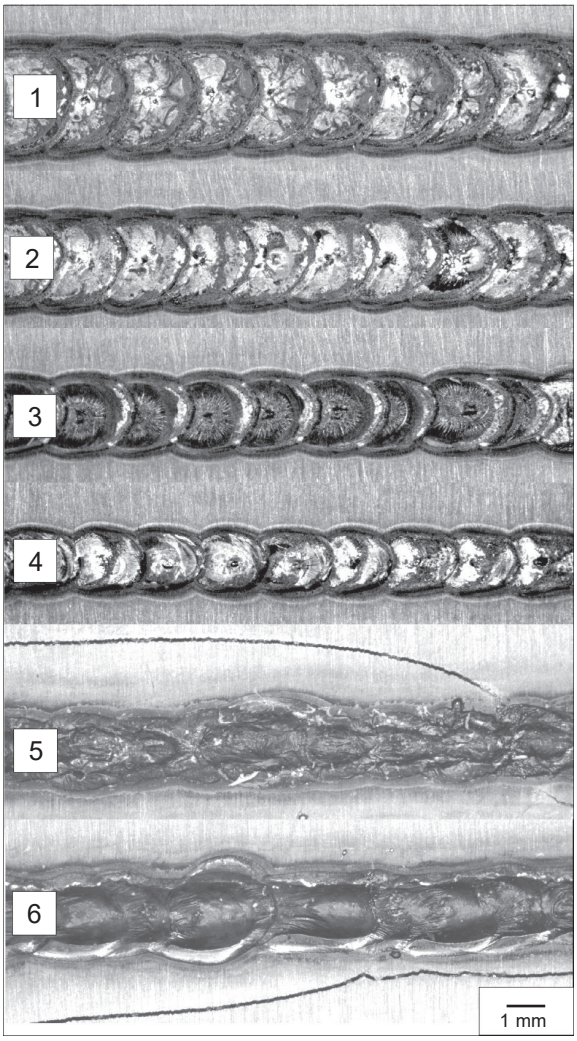

Fig. 1. Example macroscopic effects of sample remelting. Face of bands. Laser processing parameters: 1) V = 800 mm/min and Δl = 48 mm; 2) V = 800 mm/min and Δl = 44 mm; 3) V = 800 mm/min and Δl = 40 mm; 4) V = 800 mm/min and Δl = 36 mm; 5) V = 800 mm/min and Δl = 32 mm; 6) V = 800 mm/min and Δl = 28 mm

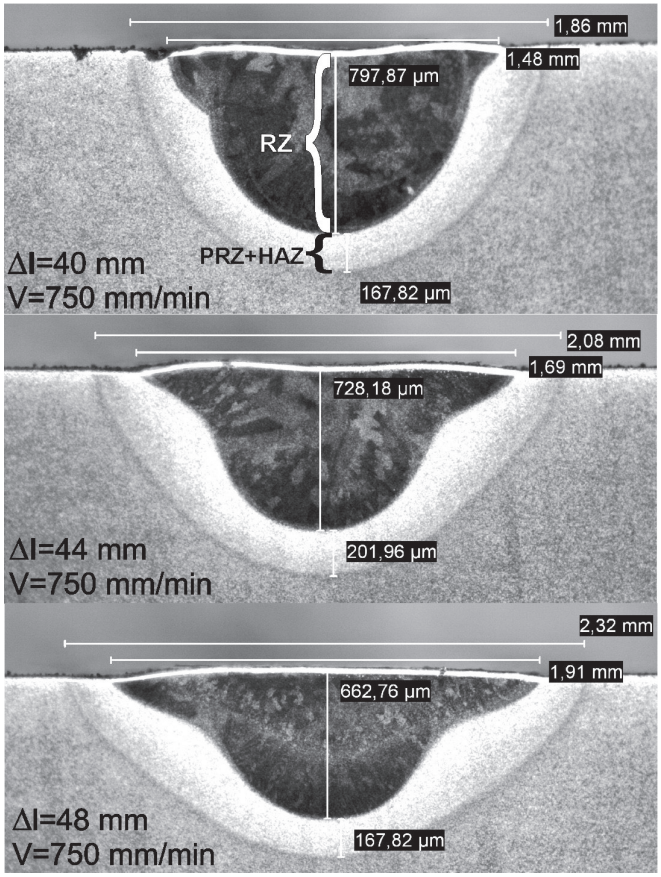

Fig. 2. Etched cross-sections of melted bands

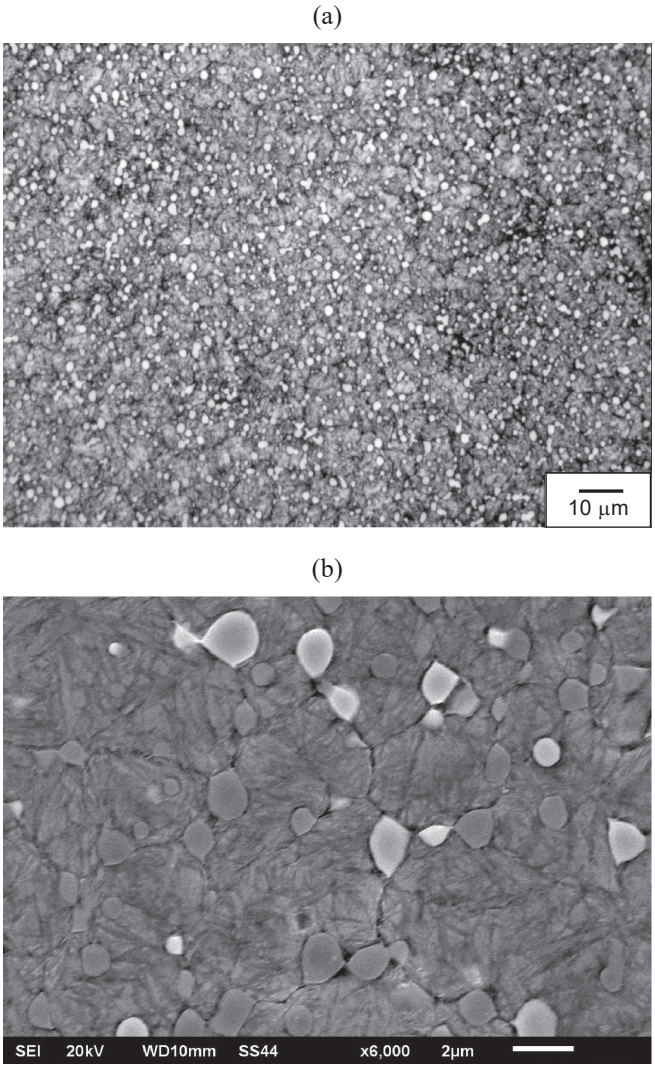

Fig. 3. Etched microstructure of P/M HSS. Light microscopy (a), SEM (b)

3.2. Microstructural investigations. The microstructure of high-speed steel in its initial state is shown in Fig. 3. The carbides were evenly distributed within the matrix and their diameter was less than 2 µm. There was no carbide banding in the material or uneven concentration of carbides in the sample volume. Such effects are often observed in high-speed steels manufactured in a conventional manner. The steel was characterized by high homogeneity in the distribution of carbides and a homogeneous chemical composition. The lack of segregation and homogeneity of the microstructure prove the isotropic nature of powder steel.

The microstructure of laser-remelted P/M HSS is shown in Figs. 4 and 5. As a result of remelting treatment, characteristic zones were formed in the surface layer, i.e. a distinctly dominant remelting zone (RZ) and the following: a partial remelting zone (PRZ) and a heat affected zone (HAZ) adjacent to the core material (BM). Similar facts were reported in [19]. The presence of distinct microdendritic structures was found in the full remelting zone (Figs. 5a, b and c). Microdendrites occurred in the entire volume of the remelting zone and were characterized by a compact structure and a very small distance between the secondary axes. The average distance between the secondary axes of dendrites was below 1 µm (Fig. 5a), which proves very high material cooling rates. A characteristic feature of the microstructure in the RZ was the dissolution of primary carbides, and the presence of extremely fine, network-like car-

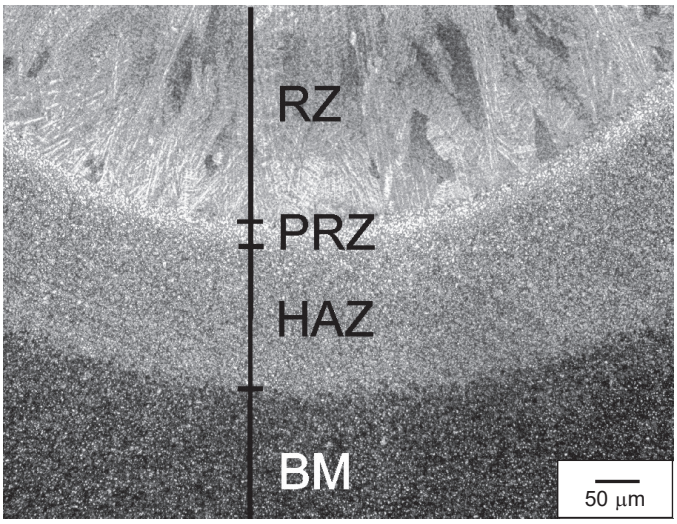

Fig. 4. Etched microstructure of melted band. V = 750 mm/min, Δl = 48 mm

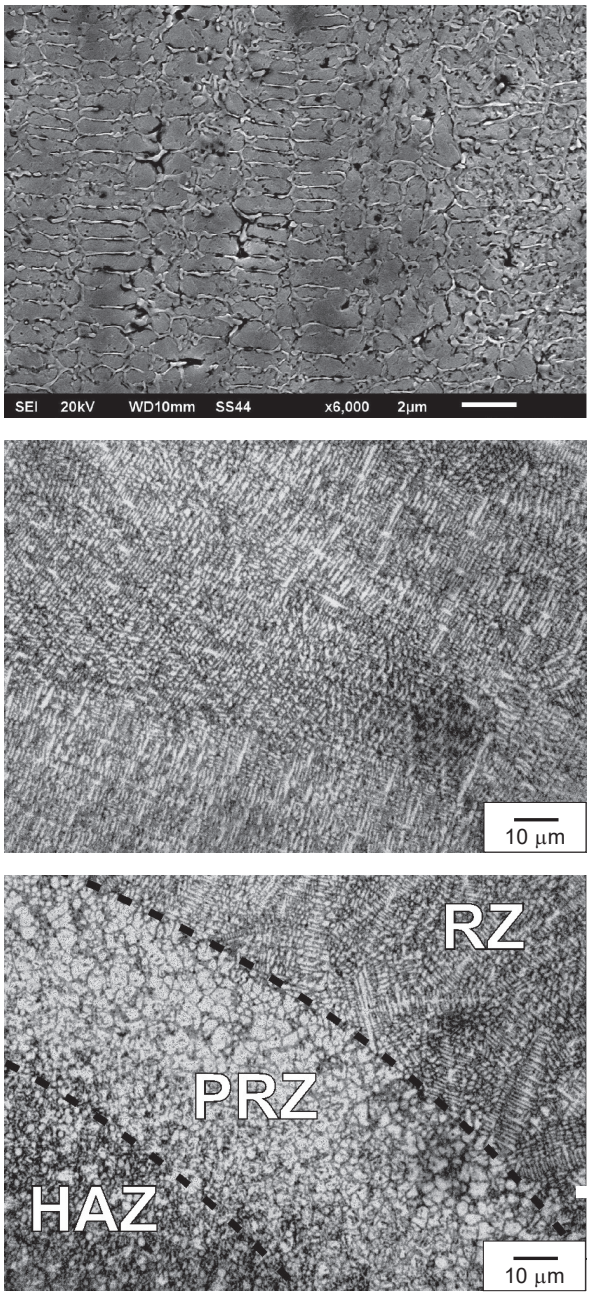

Fig. 5. Etched microstructure in RZ (a, b), in RZ, PRZ and HAZ (c). SEM (a), light microscopy (b, c). V = 750 mm/min, Δl = 48 mm

bide precipitates in the interdendritic spaces. The morphology of these carbides was different from the morphology of the primary carbides observed in the starting material. The presence of network carbide precipitates in laser surface melted high speed steel was observed by Chaus et al. [14] , among others. Between the RZ and the HAZ a narrow heterogeneous partially remelted zone was observed (Figs. 4 and 5c). The thickness of PRZ was from ∼20 to 60 µm, depending on the laser processing parameters used. The microstructure of PRZ consisted of extremely fine equiaxed grains with a diameter of 1 to 5 µm and a partial dissolution of primary carbides. Equiaxed grains dominated especially near the border with the RZ. The number of carbides in PRZ was lower than in the core, but as the core approached, the content of undissolved carbides distinctly increased.

The border between the full remelting zone and the partial remelting zone was very clear as opposed to the border between the PRZ and HAZ. In this case, there was a smooth transition from the partial remelting zone to the heat affected zone. In the wide heat affected zone, the temperature was not high enough to melt the steel and only solid-state phase transformations occurred.

The microscopic studies were enriched with fractography. The nature of material fracture constitutes one of the criteria of the initial quality assessment of the material, its homogeneity and purity, susceptibility to cracking/breaking, mechanical properties, etc. Examination of the initial steel revealed distinct isotropicity of the material and the presence of residual porosity. Completely different effects were found in the material subjected to laser treatment. A distinct microdendritic microstructure was found in the remelting zone. A characteristic effect was also the orientation of the crystallization products, reflecting the direction of heat outflow from the remelting zone. The material structure was very compact, and the residual porosity was practically eliminated, the assessment was based in this case on SEM investigations. Similar facts were reported by [2]. The fracture of the P/M HSS sample in its initial state is shown in Fig. 6a, while after remelting with a laser in Fig. 6b.

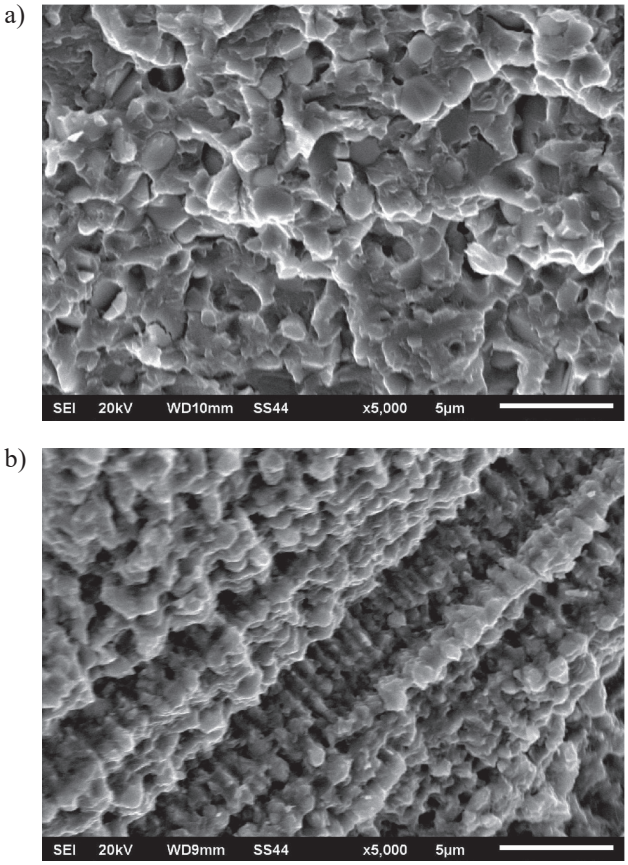

Fig. 6. Fracture in non-remelted part (a), in remelted part (b)

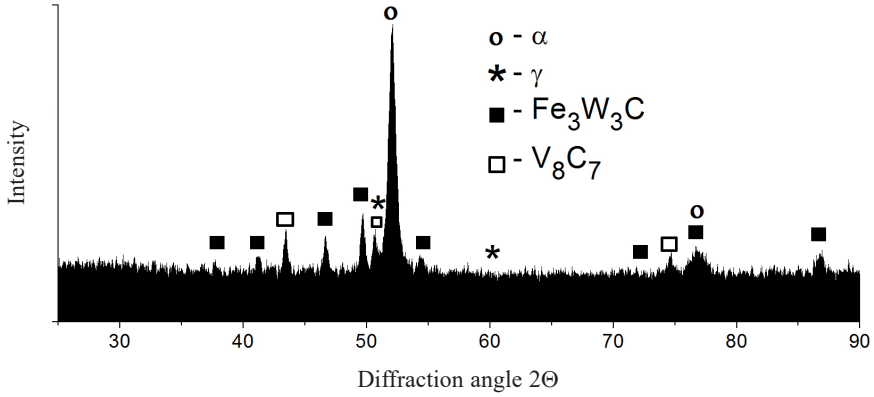

Fig. 7. Diffractogram of non-remelted P/M HSS

3.3. XRD investigations. In its initial state, i.e. after quenching and tempering, the analyzed steel had a tempered martensite structure with fine and evenly distributed carbides, MC (V_8C_7) and M_6C (Fe_3W_3C) types, and a low content of retained austenite. The retained austenite content was about 9%, as determined by X-ray diffraction. An example X-ray diffractogram of the starting material (non-remelted) is shown in Fig. 7. In the case of the remelted material, the surface of the bands was subjected to X-ray analysis. Prior to X-ray examinations, the surface of the bands was subjected to grinding with 600 grit sandpaper to eliminate surface irregularities that could affect the accuracy of the analysis. Phase composition studies revealed the presence of retained austenite, martensite, and carbide phases in the remelted material. A reduction in the intensity of diffraction reflections from the carbide phases was found in relation to the starting material, which can be explained by the complete dissolution of primary carbides in the steel matrix during laser processing and the precipitation of less numerous extremely fine, network-like carbide in the interdendritic spaces. The laser processing parameters affect not only the scope of microstructural changes, but also the type of these changes, as the cooling rate of the material changes. As is well known, the value of the Ms (Martensite start) and Mf (Martensite finish) points decrease as the cooling rate increases. A high cooling rate can therefore depress martensitic transformation and increase the content of retained austenite [16, 27].

During the research, a relationship was found between the content of retained austenite in individual samples and heat source speed V, and lack of a distinct relationship between the content of retained austenite and the value of parameter Δl. A sample remelted using Δl = 36 mm at variable speeds V = 750 mm/min, 800 mm/min and 850 mm/min was analyzed as well as a remelted sample using Δl = 48 mm, 44 mm, 40 mm and 36 mm at constant speed V = 750 mm/min. The test results are shown in Fig. 8. As can be seen, the content of

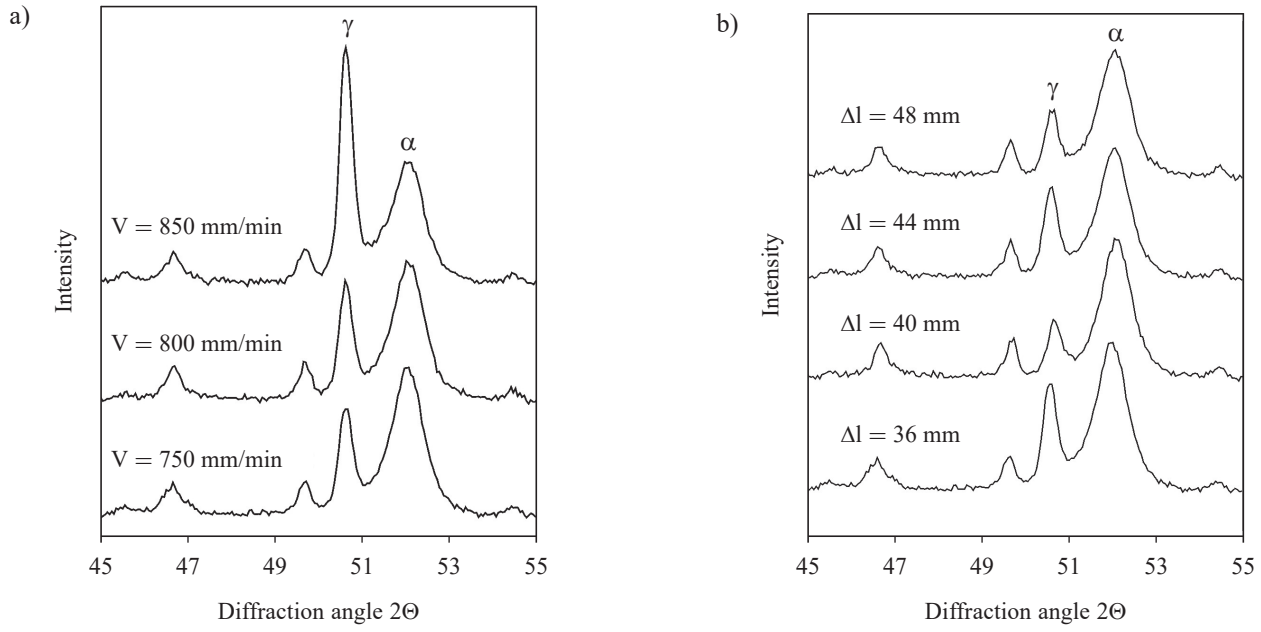

Fig. 8. Change in content of retained austenite depending on laser beam speed V at constant value of Δl = 36 mm (a); change in content of retained austenite depending on value of parameter Δl at constant speed V = 750 mm/min

retained austenite increased with an increase in the laser beam speed V and at V = 850 mm/min retained austenite became the dominant phase in the steel. However, it can also be seen that the increase in austenite content was not proportional to the increase in the value of parameter V. At V = 750 mm/min and 800 mm/min, the differences in the content of retained austenite were much smaller compared to the content of retained austenite recorded in the sample remelted at V = 850 mm/min. The impact of the parameter Δl value on the content of retained austenite was no longer so unambiguous and described by a simple relationship. The retained austenite content increased with an increase in the Δl value; however, at Δl = 40 mm a lower retained austenite content than in the other samples was observed.

3.4. Hardness results. The correlation between the applied remelting treatment parameters and hardness of P/M HSS was analyzed. The hardness measurements were made only for bands in which no disqualifying macroscopic changes were noted, which means that the bands obtained at Δl = 28 mm and Δl = 32 mm were not subjected to hardness measurements.

The analyzed samples showed a decrease in hardness in all the bands compared to the hardness of the material without treatment. The decrease in hardness was mainly caused by the presence of retained austenite in the microstructure of the remelted material. The changes in the hardness as a function of the distance from the remelted surface are presented in Fig. 9. The average hardness of the material in the full remelting zone was about 780 HV0.2, and in the heat affected zone about 870 HV0.2. The average hardness of the non-remelted material was about 960 HV0.2. Therefore, it was higher by about 23% than the hardness in the remelting zone and by about 10% higher than the average hardness of the material in the heat affected zone. A decrease in the hardness of high-speed steel after surface remelting was also found by other authors analyzing the effect of surface remelting on the microstructure and surface properties of high-speed steels [14]. In the case of

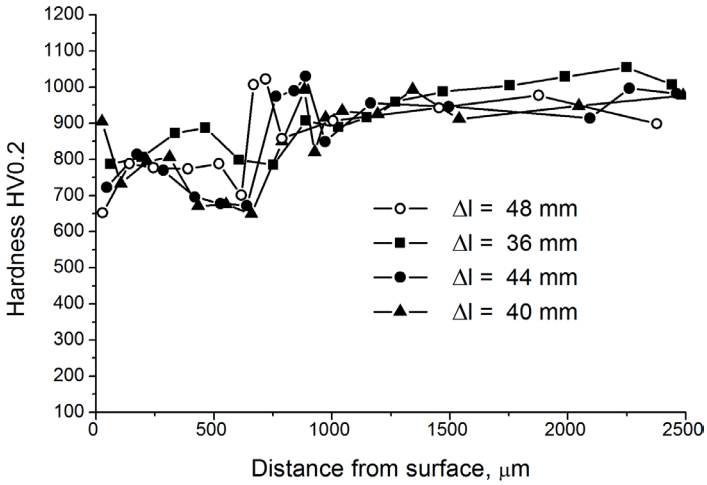

Fig. 9. Distribution of hardness as a function of distance from surface, sample No. 1 (V = 750 mm/min)

the heat affected zone, a large scatter of hardness values was also found, greater than in the full remelting zone. The analysis of hardness variability as a function of the machining parameters did not show distinct regularities between the obtained hardness and the values of the Δl or V parameters. The decrease in hardness of the remelted layer should be explained by both the presence of retained austenite and the complete dissolution of primary carbides in the steel matrix. However, it should be noted that despite such a significant content of retained austenite, the observed decrease in hardness is relatively small, which can be explained by a small grain size, precipitation of ultra-fine dispersed carbides and high solute content. According to Jurci et al. [21], the final hardness of the remelted steel is a result of the competition between the extension of solid solutions and high portion of retained austenite. In this case, an extremely high retained austenite volume fraction is the dominant factor leading to a decrease in hardness.

4. Summary

The aim of this work was to study the changes in the structure, microstructure, and hardness of P/M high-speed steel remelted by a laser beam. It was found that CO_2 laser treatment leads to significant changes in the microstructure of the surface layer of steel, whose nature and scope result from the very rapid heating of the material as well as its rapid cooling and crystallization. As a result of laser processing, a full remelting zone is formed in the surface layer of the steel, characterized by a compact microdendritic structure and the presence of extremely fine, network-like carbide precipitates in the interdendritic spaces. The primary carbide particles were completely dissolved during laser remelting treatment. The orientation of the main axes of the microdendrites corresponded to the direction of heat transfer. The remelting zone was a distinctly dominant zone in relation to the other zones formed as a result of surface treatment, i.e. the partially remelted zone and the non-remelted heat affected zone. The effects of remelting treatment, and especially the dimensions of the remelting zone, can be controlled by appropriate association of the basic treatment parameters, i.e. focus distance from the sample surface and the laser head speed. The depth of microstructural changes decreases with an increased distance of the irradiated surface from the focus of the focusing system or with an increased speed of the laser head. In turn, the remelting bandwidth decreases with a decrease in Δl, i.e. the distance of the irradiated surface from the focus of the beam focusing system, and to a limited extent also with an increase in the heat source speed. The width of the remelted surface layer obtained after laser treatment varied from 1.50 mm to 2.32 mm, and the depth varied from 0.78 mm to 1.07 mm. Remelting treatment facilitates the elimination of residual porosity of powder steels, which can contribute to the increased toughness and cutting performance of steel. The microstructure of the laser remelted steel consists of martensite, retained austenite and carbides. The retained austenite content increases with increasing V, while the influence of the Δl parameter on the retained austenite content is not unequiv-

ocal. Due to the high content of retained austenite in the remelted layer and the dissolution of primary carbides in the steel matrix, the hardness of high-speed steel after remelting is unfortunately reduced, which should be taken into account at the stage of choosing the method of processing these steels.

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