Investigation of the Technological Possibility of Laser Hardening of Stainless Steel 14Cr17Ni2 to a Deep Depth of the Surface

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Abstract: The article presents the results of a research of the process of laser hardening of steel 14Cr17Ni2 (AISI 431) by radiation of a high-power fiber laser LS-16. Assessment of the theoretically possible maximum depth in laser processing without additional beam transformations, the use of additional coatings and devices were shown. The results of experiments on increasing the depth of the hardened layer during laser processing by using scanning of the laser beam and optimally selected mode parameters without scanning are demonstrated. The influence of the number of passes on the depth of the hardened layer is investigated. The microstructure of hardened samples was studied and quantitative estimation of structural components was carried out. The microhardness of hardened samples at different modes of laser hardening was measured.

Keywords: laser hardening; depth of hardened layer; stainless steel; scanning of radiation; microstructure

1. Introduction

Steam turbine blades are responsible components of power plants [1]. They are operated in very difficult conditions that cause wear on their surface. The blades are made of chrome-plated stainless steel, which is subjected to hardening and tempering for cases where high corrosion resistance and high mechanical strength are required. At the same time, manufacturers strive to create a layer of a certain depth with the structure of martensite. In some cases, the depth of the hardened layer should reach 3.0 mm [2]. This is achieved under the condition of melting the surface and taking into account the HAZ zone and only for other steels used not for the production of blades. However, at the same time, these steels are difficult to harden or the hardness increases slightly after this treatment. Due to the fact that laser radiation has the property of directivity, it is possible to deliver a controlled amount of energy to the desired areas. This process is widely used in industry [3].

The heated layer of the material cools very quickly, causing the effect of self-cooling during the movement of the laser beam over the treated surface. A rapid decrease in temperature leads to the formation of martensite and a significant increase in hardness. Laser heat treatment of metals changes the mechanical properties of the surface. The products get resistant to corrosion, the effects of rolling friction forces, impacts, abrasion, this is required by the manufacturers of blades [4]. The surface hardening of stainless steel due to the influence of laser radiation is a deeply studied research topic. Generally, the process is carried out with a defocused beam. The results of experiments to determine the effect of laser beam defocusing on the depth and width of laser hardening zones are presented in the articles [5–9]. Numerical analysis and experimental investigations have
shown that the maximum depth of the hardened layer for stainless steel [10–12] does not exceed 1.5 mm [5,9], in some cases this is not enough for the industry. Increasing the depth of the hardened layer as a result of the laser hardening of stainless steel is an urgent process task.

The goal of the research was to develop methods for increasing the depth of the hardened layer without the use of additional coatings and devices. In this work, the dependence of the depth of the hardened zone on the linear energy applied to the sample under different conditions of the treated surface and the number of passes on the sample was investigated. The depth of the hardened zone is calculated [11] on the basis of data on the temperature on the sample surface, the properties of the processed material and the technological parameters. The results were summarized and it was concluded that it is necessary to use scanning of the laser beam to increase the depth of the hardened layer. The influence parameters scanning of the laser beam on the depth of the hardened layer was studied. The formation of macro—and microstructural features [13–15] during laser hardening was also analyzed. The influence of technological modes and surface temperature on the structure and microhardness of the created samples is revealed.

2. Materials and Methods

2.1. Numerical Experiments

Before real experiments, the maximum possible depth of the hardened layer for 14Cr17Ni2 steel was determined by calculation. Chemical composition of 14Cr17Ni2 steel according to GOST 5632-72 (RU) presented in Table 1 [10].

<table>
<thead>
<tr>
<th>Steel</th>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>Ni</th>
<th>S</th>
<th>P</th>
<th>Cr</th>
<th>Ti</th>
<th>Cu</th>
<th>Fe</th>
</tr>
</thead>
<tbody>
<tr>
<td>14Cr17Ni2</td>
<td>0.14</td>
<td>≤0.8</td>
<td>≤0.8</td>
<td>2</td>
<td>≤0.025</td>
<td>≤0.03</td>
<td>17</td>
<td>≤0.2</td>
<td>≤0.3</td>
<td>Bal.</td>
</tr>
</tbody>
</table>

It is assumed that the processing is carried out by continuous radiation with a defocused beam with a Gaussian distribution with a wavelength of 1.07 μm. The shape of the spot of the heating source on the treated surface was a circle.

At the same time, the surface of the hardened samples has no absorbing coatings. The surface of the sample does not have oxidation and deep depressions that affect the absorption coefficient of laser radiation. Numerical calculations were performed before the experiments. The parameters of the hardening mode for numerical experiments were selected in such a way that the temperature on the surface of the sample did not exceed 1600 K so that during experiments it could then be measured.

The dependence from work [11] was used as a formula for calculating the depth of the hardened layer without melting the surface of the $Z_{\text{hard}}$ (mm)

$$Z_{\text{hard}} = \sqrt{\frac{4at}{\pi}} \cdot \frac{T_{\text{surf}} - T_{\text{hard}}}{T_{\text{surf}}}$$

where, $a$—coefficient of thermal diffusivity ($\text{mm}^2/\text{s}$).

$$a = \frac{\lambda}{c \cdot \rho}$$

$\lambda = 21$—coefficient of thermal conductivity ($\text{W/(m}^\text{K})$);
$\rho = 7750$—steel density ($\text{kg/m}^3$);
$c = 500$—the variation specific heat capacity ($\text{J/(kg}^\text{K})$);
$T_{\text{surf}}$—temperature on the surface of steel (K);
$T_{\text{hard}}$—hardening temperature of steel (K);
$t$—exposure time of the heating source during hardening (s).
\[ t = \frac{D_{\text{beam}}}{V_{\text{hard}}} \]  \hspace{1cm} (3)

- \( D_{\text{beam}} \) — the diameter of the beam spot on the sample surface (mm)
- \( V_{\text{hard}} \) — hardening velocity (mm/s)

According to (2):

\[ A = 5.96 \times 10^{-6} \, \text{m}^2/\text{s} \]  \hspace{1cm} (4)

During the calculations, the beam diameter on the surface was equal to 8 mm, the hardening velocity was selected 4 mm/s. At these parameters, the exposure time of the heating source during hardening \( t = 2 \, \text{s} \).

Considering that heating and cooling are uneven in time during laser hardening. Let us accept and assume that \( T_{\text{hard}} = 1123 \, \text{K} \).

Then \( Z_{\text{hard}} = 0.704 \, \text{mm} \)  \hspace{1cm} (5)

The mode parameters of hardening were changed during calculations so that the heat input was in the range of 0.2–0.8 kW*s/mm. The calculation results showed that the maximum depth of the hardened layer does not exceed 1.0 mm.

### 2.2. Experimental Methods and Equipment

The calculation result was tested experimentally. For this purpose, rectilinear tracks were applied to samples with a thickness of 20 mm.

Before the experiments, the samples were degreased and the surface of the samples was sanded to remove oxides and depressions or scratches to stabilize the radiation absorption conditions.

Laser processing was carried out using a laser technological complex with continuous radiation with a wavelength of 1.07 µm generated by a 16 kW fiber ytterbium laser LS-16 (IPG Photonics, Oxford, MA, USA). The surface temperature of the sample was measured during hardening in the laser beam treatment zone using an optical pyrometer CT Laser 3MH2-SF (Optris, Berlin, Germany). The pyrometer operates in the range of 200–1500 °C, the distance between the measuring target of the pyrometer and the center of the laser beam spot was 1 mm. This scheme allows you to measure the temperature at the level of the hardening temperature without melting for the selected steel grade. Location of the laser head YW50 ZK (Presitec, Gaggenau, Germany), the pyrometer and the sample during the experiments can be estimated from Figure 1.

![Figure 1. The location of the optical instruments during the heat treatment of the sample.](image)

The laser head YW50 ZK had a DC-ILV scanner with mode parameters of scanning in the transverse hardening direction: frequency 50–800 Hz, amplitude 2.0–12.0 mm.
2.3. Methods of Preparation and Research of Metallographic Sections

The metallographic specimens were made from the created samples with tracks after laser processing. The hardened samples were prepared for the manufacture of metallographic specimens by forming them in a phenolic compound, grinding and polishing. The metallographic analysis was performed by optical light microscopy. The microstructure was studied using a Leica DMi8 inverted microscope (Leica Microsystems, Wetzlar, Germany) equipped with an «Axalit» image analyzer (Axalit, Moscow, Russia). The microstructure was detected using the Kalling reagent (20 mL H₂O + 20 mL CH₃CH(OH)CH₃ + 20 mL HCl + 4 g CuCl₂) with an exposure time of 20–30 s. Measurements of the hardened layer and depth of penetration were made by the «Digimizer» software using macrosections. The microstructure in different areas of hardened specimens was detected using Berach’s reagent (80 mL H₂O + 20 mL HCl + 1 g K₂S₂O₅) with an exposure time of 1–2 min. A different ratio of martensite, ferrite and retained austenite is formed depending on the parameters of the processing mode. The level of contrast in grayscale is sufficient for binarization at a given threshold of brightness and determination of the volume fraction of phases according to ASTM E1245 [11] in automated mode. The content of retained austenite in the samples hardened at different modes was determined by the method based on etching with Berach’s reagent and image analysis using the software «ImageJ». Scanning electron microscopy (SEM) Tescan Mira3 (TESCAN, Brno, Czech Republic) equipped with an Energy Dispersive X-ray (EDX) detector and the console Oxford AZtec (Oxford Instruments NanoAnalysis, Abingdon, United Kingdom) was used. The SEM images were obtained on polished samples using the backscattered electron (SE) detector.

Studies of phase identification of the samples before and after laser hardening were conducted with an X-ray diffractometer (XRD) D2 Phaser (Bruker, Karlsruhe, Germany), with CuKα radiation (wavelength = 1.54184 Å), measured in the 2θ range from 30° to 100° operated at 30 kV and 10 mA with a 2θ step size of 0.02 and a dwell time of 0.1 section. DIFFRAC.EVALUATION PACKAGE (Bruker, Karlsruhe, Germany) was used to semi-quantitatively determine the weight fraction of constituents.

2.4. Method of Measuring Hardness and Microhardness

Hardness and microhardness measurements were carried out on microhardness tester series FM-310 (Future Tech, Kawasaki, Japan) with a load of 2000 g and 300 g a Vickers equipped with an image analyzer «Thixomet Pro» (Thixomet, St. Petersburg, Russia). The hardness in the depth of the hardened layer was determined at a load of 2000 g, offset from the surface by 50 µm, and with a step between the prints of 150 µm, Figure 2.

Figure 2. The scheme of hardness measurements.

3. Results and Discussion

3.1. Experiments without Scanning Laser Radiation

The first series of experiments on laser heat treatment of samples made of 14Cr17Ni2 steel was carried out according to Table 2.
The closest value of the surface temperature measured as a result of experiments to the hardening temperature (1373 K) was created in No. 2 (see Figure 3). When the surface temperature exceeds this value (modes No. 1, 3, 4), local melting of the surface is observed. It is caused by an unequal distribution of power over the heating spot, which causes uncontrolled heat input into the material. After laser processing, microspecimens were manufactured from the samples. The track created using the parameters of mode No. 2 and the microspecimen of the sample are shown in Figure 3a,b. A hardened zone and a heat-affected zone (HAZ) were identified on the microspecimens.

![Figure 3. The microstructure of the hardened sample, mode No. 2: (a) the image of the hardened track; (b) the image of the microspecimen.](image)

Mode No. 4 was selected as a result of the microspecimens’ measurements. The maximum depth was reached on it, where phase transformations occurred, causing an increase in microhardness and hardening of the surface. The depth was 1.25 mm, and the width was 7 mm, and for mode No. 2, the depth of the hardened layer was 0.75 mm. This is less than 1.5 mm indicated in the works of other researchers, but this depth was obtained for a different steel grade and a case with surface melting.

Then microhardness measurements were made. The average value in the hardened zone is HV² = 345, in the HAZ HV² = 321, and in the base metal zone HV² = 290. An increase of 1.2 times in microhardness in the hardened zone without melting of the treated surface is observed as a result of laser treatment. The total depth of microhardness including the zone of thermal influence in comparison with the base metal is more than 1 mm. In the hardened zone, a martensitic–ferritic structure was revealed, which alternates with layers of soft austenite.

### 3.2. Experiments with Scanning Laser Radiation

Scanning of the laser beam was applied to increase the depth of the hardened layer. This increased the exposure time of the laser beam over the entire surface of the sample, but at the same time, the heating became more uniform over the entire surface. Such a controlled heat input should allow increasing the depth of the hardened zone without melting the surface.

### Table 2. Parameters of the mode of experiments on laser heat treatment.

<table>
<thead>
<tr>
<th>No.</th>
<th>α (°)</th>
<th>β (°)</th>
<th>Dsurf, (mm)</th>
<th>Qn, (kW·s/mm)</th>
<th>Tsurf, (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>10</td>
<td>38</td>
<td>8</td>
<td>0.22</td>
<td>1473</td>
</tr>
<tr>
<td>2</td>
<td>10</td>
<td>38</td>
<td>8</td>
<td>0.4</td>
<td>1373</td>
</tr>
<tr>
<td>3</td>
<td>10</td>
<td>38</td>
<td>8</td>
<td>0.43</td>
<td>1523</td>
</tr>
<tr>
<td>4</td>
<td>10</td>
<td>38</td>
<td>8</td>
<td>0.46</td>
<td>1522</td>
</tr>
</tbody>
</table>

where α—the angle of deviation of the laser head from the vertical, [°]; β—the angle of deviation of the optical axis of the pyrometer from the horizontal plane where the sample is located, [°]; Dsurf—the diameter of the laser beam on the surface of the processed sample, [mm]; Qn—heat input, [kW·s/mm]; Tsurf—the measured temperature on the sample surface in the treatment area, [K].
Experiments on laser heat treatment of steel samples in the second case were carried out according to the same arrangement of the beam and pyrometer relative to the sample surface. During the experiments, the beam was defocused and scanned over the sample surface with the maximum possible amplitude of 9.6 mm, at a scanning frequency of 100 Hz. The mode parameters were set according to Table 3.

<table>
<thead>
<tr>
<th>No.</th>
<th>Type of Beam Scanning</th>
<th>( Q_n ) (kW*s/mm)</th>
<th>( T_{surf} ) (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>triangle</td>
<td>0.73</td>
<td>1473</td>
</tr>
<tr>
<td>6</td>
<td>triangle</td>
<td>0.78</td>
<td>1553</td>
</tr>
<tr>
<td>7</td>
<td>triangle</td>
<td>0.76</td>
<td>1523</td>
</tr>
<tr>
<td>8</td>
<td>sinus</td>
<td>0.73</td>
<td>1243</td>
</tr>
</tbody>
</table>

The linear energy and the type of beam scanning were changed during this series of experiments. The maximum recorded temperature on the surface without melting is 1473 K (mode No. 5). The «triangle» was chosen as the type of beam scanning that provides a more stable result for the entire length of the track. Unequal heating zones occurred in all experiments when using the «sinus» type of beam scanning.

A microspecimen was made from the treated sample (Figure 4a) to measure the size of the heat treatment zones, microhardness and study the phase composition of the hardened zone Figure 4b.

The hardened zone, the HAZ and the zone of the base metal were identified as a result of measurements of a microspecimen made from a sample with a track created on the parameters of mode No. 5. Then, microhardness measurements were made. The average value in the hardened zone is \( HV^2 = 331 \), in the HAZ \( HV^2 = 267 \), and in the base metal zone \( HV^2 = 244 \). The width of the processing zone has increased from 7 mm for the processing mode without scanning to 17 mm for processing with scanning of laser radiation according to the «triangle» type.

After that, the data of calculating the depth of the hardened layer and the data of hardness measurements in the samples after the experiments were compared.

3.3. Comparison of Calculations and Experimental Results

The graph of the dependence of the depth of the hardened layer on the surface temperature which varies depending on the parameters of the applied radiation was created (Figure 5).
The figure shows that as the surface temperature increases, the depth of the hardening layer $Z_{\text{hard}}$ increases, and the experimental values of $Z_{\text{hard}}$ slightly exceed the expected calculated values of $Z_{\text{hard}}$. At the same time, the discrepancy between the calculated and experimental values is minimal for the temperature areas below the melting temperature, which suggests that in the temperature area between the hardening temperature and the melting temperature of the selected steel, the calculated formula for $Z_{\text{hard}}$ should be used.

The mode parameters for the further experiments were chosen on the basis of the $Z_{\text{hard}}$ calculation. Laser beam scanning was used to increase the depth of the hardened layer. This increased the exposure time of the laser beam to the entire surface, but the heating became more uniform over the entire surface, this controlled heat input should allow increasing the depth of the hardened zone without melting the surface.

Experiments on laser heat treatment of steel samples in the second case were carried out according to the same scheme of the beam and pyrometer arrangement relative to the surface of the sample. At defocusing of the beam and its scanning along the sample surface with the maximum possible beam scanning amplitude of 9.6 mm and scanning frequency of 100 Hz, the mode parameters were set according to Table 3.

### 3.4. Microstructure Analysis

Figure 6 shows the Kalling reagent microstructure in different areas of the hardened sample.

The structural components of the base metal represent tempered martensite and δ-ferrite in all samples Figure 6d. The microstructure in the HAZ (Figure 6c) represents martensite and δ-ferrite, in the quenched zone Figure 6b—martensite and δ-ferrite and its partial transition to martensite component. In the samples where melting of the upper boundary was observed as a result of temperature overheating, there is partial decay of δ-ferrite and partial formation α-ferrite Figure 6a, martensite forms a granular mixture. The average microhardness of martensite in the hardened zone was (440–480 HV₀.₃), in the base metal (300–330 HV₀.₃), δ-ferrite in the hardened zone (250–278 HV₀.₃), in the base metal 220–250 HV₀.₃). Extended areas of δ-ferrite are preserved at ambient temperature, the effect of $\delta \rightarrow \gamma$-conversion on the subsequent $\gamma \rightarrow \alpha$-conversion in 14Cr17Ni2 steel subjected to laser hardening. The stainless steel has a large biphasic region (δ + γ), and significant δ-ferrite content can persist at ambient temperature. The $\gamma$-phase formed was metastable and converted to $\alpha$-phase upon further cooling. Partial formation of high-energy interfaces $\delta/\gamma$, which contributed to $\gamma$-to $\alpha$-ferrite conversion occurring at a relatively higher temperature, and to some extent reduced the hardness of laser hardening.
Figure 6. Microstructure in different areas: (a) molten zone; (b) hardened layer; (c) HAZ; (d) base metal.

Berach’s etching allows sufficient contrast of ferrite, martensite, and austenite white areas Figure 7. Determinations of the volume fraction of phases in the automated mode Figure 7e. The proportion of retained austenite and some technological modes of hardening are shown in Table 4.

A small content of retained austenite γ-phase (white color) was presented in the structure of Figure 7 [12]. After hardening, the preservation of large areas of δ-ferrite is observed. In samples 5, 6, 7, 12, 14 due to high-temperature gradients, melting of the upper boundary of the hardened zone. Due to high surface temperature, partial decomposition of δ-ferrite into α-ferrite and martensite occurred, the structural components in these areas were martensite and ferrite. In the state after hardening the δ-ferrite is preserved. As a consequence, grains of δ-ferrite surrounded by lath martensite are preserved in the samples where the melting of the upper boundary of the hardened zone did not take place [13]. Therefore, the microstructure of the melting zone after hardening consisted of rack martensite, coarse δ-ferrite and α-ferrite and partial content of γ-austenite [14–18]. The content of martensite throughout the hardened zone was 50–55%, the second phase ferrite and a small proportion of retained austenite Table 4. The data obtained for retained austenite were confirmed by a semi-quantitative method in X-ray diffraction analysis.

After hardening with one pass, the average microhardness in the hardened layer is 323 HV with $Q_n = 0.28$ kW*s/mm and 294 HV with $Q_n = 0.42$ kW*s/mm. The microstructure represents δ-ferrite and martensite.

After hardening with two passes, the average microhardness in the hardened layer is 303 HV with $Q_n = 0.28$ kW*s/mm and 254 HV with $Q_n = 0.42$ kW*s/mm. The re-scanning
increases the depth of the hardened layer but decreases the average microhardness. After re-hardening, the upper part of the sample is melted and the fraction of retained austenite increases. The microstructure presents δ-ferrite, with the partial formation of α-ferrite in the melted zone and martensite, the structural components in these areas are martensite and ferrite.

Figure 7. Microstructure of the hardened area, (a) No. 4; (b) No. 5; (c) No. 6; (d) No. 14; (e) No. 12; (f) automatic identification of austenite.
Table 4. Influence of the linear energy on the depth of hardened layer and structural components.

<table>
<thead>
<tr>
<th>No.</th>
<th>$Q_n$, (kW*s/mm)</th>
<th>Type of Beam Scanning</th>
<th>Melting Zone, (mm)</th>
<th>Hardened Zone, (mm)</th>
<th>HAZ, (mm)</th>
<th>Retained Austenite, $\gamma$ (wt. %)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.22</td>
<td>No scan</td>
<td>–</td>
<td>0.35</td>
<td>0.75</td>
<td>–</td>
</tr>
<tr>
<td>2</td>
<td>0.40</td>
<td>No scan</td>
<td>–</td>
<td>0.75</td>
<td>1.2</td>
<td>0.1</td>
</tr>
<tr>
<td>3</td>
<td>0.43</td>
<td>No scan</td>
<td>–</td>
<td>0.65</td>
<td>1.25</td>
<td>–</td>
</tr>
<tr>
<td>4</td>
<td>0.46</td>
<td>No scan</td>
<td>–</td>
<td>1.25</td>
<td>1.6</td>
<td>2.2</td>
</tr>
<tr>
<td>5</td>
<td>0.73</td>
<td>Triangle</td>
<td>0.17</td>
<td>1.15</td>
<td>1.85</td>
<td>0.35</td>
</tr>
<tr>
<td>6</td>
<td>0.78</td>
<td>Triangle</td>
<td>0.46</td>
<td>1.4</td>
<td>2.2</td>
<td>0.85</td>
</tr>
<tr>
<td>7</td>
<td>0.76</td>
<td>Triangle</td>
<td>0.38</td>
<td>1.33</td>
<td>2.1</td>
<td>0.5</td>
</tr>
<tr>
<td>8</td>
<td>0.73</td>
<td>Sinus</td>
<td>–</td>
<td>0.42</td>
<td>1.06</td>
<td>–</td>
</tr>
<tr>
<td>9</td>
<td>0.28</td>
<td>No scan</td>
<td>–</td>
<td>0.3</td>
<td>0.6</td>
<td>–</td>
</tr>
<tr>
<td>10</td>
<td>0.42</td>
<td>No scan (2 passes)</td>
<td>–</td>
<td>0.7</td>
<td>1.1</td>
<td>0.1</td>
</tr>
<tr>
<td>11</td>
<td>0.28</td>
<td>No scan (4 passes)</td>
<td>–</td>
<td>0.4</td>
<td>0.73</td>
<td>0.4</td>
</tr>
<tr>
<td>12</td>
<td>0.42</td>
<td>No scan (2 passes)</td>
<td>0.11</td>
<td>1.3</td>
<td>1.7</td>
<td>1.6</td>
</tr>
<tr>
<td>13</td>
<td>0.28</td>
<td>No scan (4 passes)</td>
<td>–</td>
<td>0.78</td>
<td>1.4</td>
<td>0.2</td>
</tr>
<tr>
<td>14</td>
<td>0.42</td>
<td>No scan (4 passes)</td>
<td>0.47</td>
<td>1.6</td>
<td>2.2</td>
<td>0.7</td>
</tr>
</tbody>
</table>

3.5. Microhardness Analysis

Laser hardening with four passes positively affects the depth of the hardened layer increasing it, the microhardness also increases. Average microhardness in the hardened layer is 322 HV$^2$ with $Q_n = 0.28$ kW*s/mm and 319 HV$^2$ with $Q_n = 0.42$ kW*s/mm. After four hardening passes the melting in the upper part of the sample increases, the share of retained austenite decreases due to the cyclic effects of the laser source. The microstructure represents segregation in areas δ-ferrite, with partially formed α-ferrite in the melted zone and martensite matrix, the structural components in these areas are martensite and ferrite. Figure 8 shows the graph of the hardness of the hardened samples.

High hardness was obtained in modes No. 4, 6, 7, Figure 8, also on these samples the greatest depth of the hardened zone was obtained. In multipass hardening, the highest hardness was obtained in the mode with two passes and at linear energy of 0.28 kW*s/mm, mode No. 11. The greatest depth of the hardened zone was obtained at a rate of energy input of 0.42 kW*s/mm, mode 12. At hardening with four passes, the greatest depth and high hardness was reached with the rate of energy input 0.28 and 0.42 kW*s/mm mode No. 13 and 14, Figure 8.

3.6. XRD Results Analysis

Figure 9 shows the XRD analysis of the obtained samples in the initial state and after hardening. The microstructures obtained on a scanning electron microscope showed the presence of some carbides. While $M_{23}C_6$ (M = Fe, Cr) particles with an average size of 2 µm are preferentially clustered in bands along ferrite grain boundaries. The X-ray diffraction in Figure 9 confirms the presence of retained austenite and carbide $Cr_23C_6$ have in the (FCC) and α-ferrite (BCC) [19]. On the X-ray diffractogram, δ-ferrite is not detected. This may be due to the fact that the Fe is superimposed on the δ-ferrite peak. After the hardening, the amount of δ-Fe phase was significantly reduced due to the disintegration into γ-Fe. The appearance of γ-Fe in the quenched layer can negatively affect the hardening layer and reduce hardness.
In this study, we investigated the microstructure and hardness of a specific steel after laser hardening. The optimum microstructure after laser hardening for this steel is a ferrite–martensite structure. The study focused on a 35CrMo4 steel, which was laser hardened under various conditions to achieve different microstructures.

### Results

1. **Hardness Analysis**
   - Hardness graph of hardened samples (Figure 8).
   - The greatest depth of hardening and hardness on samples without scanning is approximately 333 HV2.
   - After hardening with one pass, the average microhardness in the hardened layer is 322 HV2 with Qn = 0.28 kW*s/mm and 319 HV2 with Qn = 0.42 kW*s/mm.

2. **Microstructure**
   - SEM micrographs showing M23C6 carbides distributed inside the ferrite matrix (Figure 9a).
   - X-ray diffraction pattern that confirms the crystallographic structure (Figure 9b).

### Conclusions

- Laser hardening with four passes positively affects the depth of the hardened layer.
- After re-hardening, the upper part of the sample is melted and the fraction of retained austenite increases. The microstructure presents phase ferrite and a small proportion of retained austenite.

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### Author Contributions

Conceptualization, V.S. and I.T.; methodology, V.S., A.A.; validation, I.T., and A.A.; writing—original draft preparation, V.S., R.M., I.T.; writing—review and editing, V.S. and R.M.; visualization, V.S. and R.M.; supervision, I.T. and A.A. All authors have read and agreed to the published version of the manuscript.

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**Figure 8.** Hardness graph of hardened samples.

**Figure 9.** (a) SEM micrographs showing M23C6 carbides distributed inside the ferrite matrix. (b) SEM-EDX mapping the molar fraction of Cr over the area specified in (a). (c) X-ray diffraction pattern that confirms the crystallographic structure.
4. Conclusions

The melting of the upper boundary of the hardened layer will adversely affect the performance properties. The melting of the upper boundary of the hardened layer begins at a rate of energy input above 0.73 kW*s/mm and at a surface temperature of 1473 K during the use of triangle scanning (mode 5–7). The melting of the upper boundary of the hardened layer begins with a repeated pass and increases with subsequent ones at a rate of energy input of 0.48 kW*s/mm without scanning (mode 12, 14).

The greatest depth of hardening and hardness on samples without scanning is achieved in mode 4, the average hardness of the hardened zone is ~355 HV². The greatest depth of hardening and hardness on samples with triangular scanning is achieved in mode 7, despite the high depth of the molten zone, the average hardness of the hardened zone in this mode is ~403 HV². The greatest depth of hardening and hardness on samples with multipass hardening is achieved in mode 14, the average hardness of the hardened zone is ~333 HV².

The optimum microstructure after laser hardening for this steel is a ferrite–martensitic structure with a content of martensitic component more than 50% and with a minimal amount of retained austenite, these conditions correspond to modes: 4, 7, 14.

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