

Creation of wear-resistant layers on steels using TIG electric arc surface remelting process with applying CaCN₂-based nitriding powder

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Research Article

Keywords: TIG surface remelting, nitriding powder, hardness, wear resistance

Posted Date: August 2nd, 2022

DOI: <https://doi.org/10.21203/rs.3.rs-1878885/v1>

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Abstract

Tungsten inert gas (TIG) electric arc welding process was used for surface remelting of nitriding powder applied on selected steel grades. The influence of remelting on the chemical composition and microstructure changes in the remelted area of selected steels (25CrMo4, 30CrMoV9, 41CrAlMo7) with different content of nitride-forming elements (Al, V) was investigated to improve hardness and abrasion wear resistance. Nitriding powder Pulnierpulver based on calcium cyanamide (CaCN_2) was used in remelting. Hardness measurements and determination of abrasive wear resistance on an abrasive cloth with Al_2O_3 particles were performed. The microstructures of the remelted layers, as well as the worn areas, were observed by SEM. The presence of nitrogen in the remelted layers was proved by EDX analysis. A significant increase of hardness and abrasive wear resistance was achieved up to a depth of 1–1.5 mm from the surface in the case of all steels through remelting process. These results obtained can be attributed to the significant effect of nitrogen on the hardenability increasing of remelted layers and alloying martensite with nitrogen. The most significant growths of both parameters investigated were achieved in 25CrMo4 steel, for which the most significant nitrogen enrichment was found. The presented process of TIG surface remelting with powders containing a particular element represents a cheap, affordable, and fast way of forming surface layers with improved hardness and wear resistance.

1 Introduction

Abrasive wear is one of the most common mechanisms operating machine parts. Gradual material loss from the functional surfaces of components leads to a deterioration of their functionality and service life reduction [1, 2]. The abrasive wear process is influenced by several factors, material factors being the most important. They are the chemical composition (the content of elements enabling the formation of hard structures) [3] and microstructure (presence of hard phases, their shape, size, distribution, and proportion) [4, 5], which have a direct effect on the properties determining the wear progress (hardness, wear resistance). Iwaszko and Kudła [6] present a significant influence of the microstructure (grain refinement) created by rapid cooling after friction stir processing of an aluminium alloy on its hardness and wear resistance.

Chintha [7], based on several studies, states that abrasion resistance is linearly dependent on hardness. Several mechanisms increasing the dislocation motion energy demand can significantly increase hardness. Kostryzhev [8] provides an overview of the mechanisms of metallic materials strengthening. Such mechanisms include, for instance, strain hardening, alloying, precipitation, grain refinement, and phase composition. Misra et al. [9] present a method of strengthening (the hardness increasing) multilayer composites by controlling the thickness of the individual layers. Daghbouj et al. [10] describe the deformation reduction due to increased mobility of vacancies and interstitials in a multilayer metallic material.

Various methods are used to increase the wear resistance of steel machine parts. Most of them are based on the formation of surface layers. The surface layer formation results either from the chemical

composition or a change in the microstructure of the part surface layers. A detailed overview of the available methods is given in [11]. Chemical-thermal treatment methods are the most widely used methods of surface layers with specific properties formation with the chemical composition changes. These are based on diffusion processes of suitable elements, mostly with smaller atomic sizes (e. g. carbon, nitrogen, boron). However, these technologies are often energy and time-consuming. The layers formed are very thin, limiting their operation in conditions of intense abrasive wear.

Nitriding is one such technology. The steel surface layer is enriched with nitrogen during nitriding to achieve a microstructure containing nitrogen-based hard phases. The phase composition of the nitrided layers significantly depends on the nitriding temperature [12]. Li et al. [13] found that in plasma nitriding of austenitic steel, the hardness achieved depends on the nitriding time. Nitrided layers are resistant to fatigue and wear and have good sliding properties and corrosion resistance [11, 14].

Conventional nitriding, most often in a gaseous atmosphere, is very energy and time-consuming (heating to temperatures of 500–600°C for several tens of hours). The hardness of the nitrided layers reaches the value of 800–1200 HV and significantly increases wear resistance. However, the formed layer thicknesses usually reach only a few tens of micrometres [15–17]. Kurz [18] describes nitriding using nitriding powder and an activator, resulting in a significant reduction of nitriding time, achieving similar properties of the nitriding layer as those formed in a salt bath. Several authors present the use of nitriding to improve the properties of primary layers produced by various technologies [19–21]. Orečný et al. [22] significantly increased wear resistance by nitriding high-temperature tempered tool steel.

The second method of forming layers with specific properties on the part functional surfaces is to apply hard-facing materials to a pre-processed surface. The technologies differ in the principle of layer formation, the time required to form a layer with the required properties, the properties of the resulting layer, etc. Müller et al. [23] compared the wear resistance of carbide and martensitic weld materials with better results for carbide materials forming an austenitic matrix. Coronado et al. [24] did not find a dependence of abrasion wear resistance on hardness when comparing four hard-facing materials. They consider the presence of carbides and the matrix microstructure to be the most critical factors in increasing the resistance to abrasive wear. Krolicka et al. [25] reported similar conclusions by describing the effect of hard-facing microstructure on abrasive wear mechanism. Xu et al. [26] discussed the influence of selected elements on the resulting properties of the surface layer formed by plasma deposition. They found that the carbon content had the most significant effect on the hardness and wear resistance of the formed surface layer. The effect of Mo and V on these properties was only minor. Sebek et al. [27] achieved the dendritic character of a matrix formed of fine martensite and austenite by laser remelting of X37CrMoV5-1 steel. They achieved supersaturation of the solid solution with alloying elements, which significantly affected hardenability. The remelted microstructure showed better wear resistance than the not remelted one.

Significant reduction of energy and time requirements of layers enriched with a particular element (or elements) formation can be achieved by remelting the material surface layers with a tungsten inert gas

(TIG) electric arc in an environment with an increased concentration of the element (or several elements), contained in a powder with a suitable chemical composition/microstructure. Dyuti et al. remelted Ti powder [28] and Ti + Al powders [29] by TIG in shielding atmosphere N. A dendritic microstructure formed by titanium nitrides or nitrides and intermetallic phases based on Ti and Al was formed. A significant increase in the wear resistance of steels can also be achieved by remelting carbide powders (WC, SiC, TiC) by TIG [30–32]. Xu et al. [33] used a TIG process to remelt a flux cored wire filled with a powder of suitable chemical composition to form a cermet layer on low carbon steel substrate while achieving similar properties compared to the same type of cermet produced by sintering. Thanks to remelting, the microstructure of the cermet formed by the TIG process was even more compact and achieved higher wear resistance. The TIG process can also be used to modify the properties of layers pre-formed by other technologies. The TIG process can also be used to modify the properties of layers pre-formed by other technologies [34–36].

This paper presents the results of TIG electric arc surface remelting of selected steel grades in a nitrogen-rich environment to saturate the remelted area with nitrogen, creating conditions for the formation of a microstructure with increased hardness and wear resistance. Steels used the material for remelting are expected to achieve a hardening after nitrogen saturation. Two criteria were considered when selecting the steels to include in the study. The steels should be suitable for the process of nitrogen-induced strengthening in remelted layer. For this reason, steels containing nitride-forming elements (Cr, Al, V) were selected. The steels also should be of interest for practical application. Selected steels are commonly available and are used to produce components with requirements for high strength and toughness, as well as high wear resistance.

In the design of the experiment, the assumption was formulated that the dissociation and ionisation of the agent are achieved using the electric arc. These will enable the initiation of diffusion processes in the surface layer of the remelted steel. It assures appropriate conditions for the penetration of nitrogen atoms into the crystal lattices of metal elements contained in the remelted layer, expecting an improvement in hardness and wear resistance. The work builds on previous research on the part of the authors, in which the method of surface remelting of steels by an electric arc in the presence of a boron environment was applied. By remelting B_4C powder, carboborides were formed in the remelted layers, significantly increasing the hardness and wear resistance [37].

2 Methods

In the described experiment, selected grades of steels were used, the chemical composition of which creates preconditions for the formation of nitrogen-induced strengthening. These are primarily steels used for nitriding. The type of the tested steels with chemical composition describes Table 1.

Pulnierzpulver nitriding powder from AZ Prokal Ltd. Brno (Czech Republic) was used with the main component calcium cyanamide ($CaCN_2$).

The process of saturating the surface layers of the used steel was carried out by remelting the nitriding powder Pulnierpulver with an electric arc. The nitriding powder was applied to the clean metal surface of the remelted sample. The thickness of the applied layer was 1 mm. Before application, the powder was moistened with distilled water to get a pasty consistency. The samples were then heated in an oven at 50 °C for 20 minutes. It created a solid layer of powder, preventing the powder from blowing off with the shielding gas during remelting. The sample shape was a cylinder with a diameter of \varnothing 20 mm and a height of 20 mm. The entire surface area of the samples was remelted, three samples for each steel grade.

Remelting the substrate with the layer of nitriding powder was realised using the technology of TIG welding in an inert shielding atmosphere. The welding inverter SMARTY TX 160 Alu (Air Liquide Slovakia Ltd., Nitra, Slovak Republic) was used as a heat source during remelting. The remelting process took place in the shielding atmosphere of 99.996 % argon (argon 4.6) at a gas flow of $10 \text{ l}\cdot\text{min}^{-1}$ and a welding current of 110 A. Remelting was carried out by moving the torch manually, so the speed of movement of the torch is not defined.

In order to evaluate the expected changes in the chemical composition of the steels due to remelting in the nitriding powder, all steel grade samples were remelted in the shielding atmosphere of argon 4.6 with no nitriding powder. In addition, all steel grade samples not remelted were used as a basic standard. The properties of both types of standard samples were determined by the same methods as the properties of the samples remelted in a nitriding powder environment.

The remelted samples were cut perpendicularly to the remelted layer (vertically) into two uneven parts (a smaller part – 1/3 of the sample diameter, a bigger part – 2/3 of the sample diameter). Smaller samples were used for hardness and metallographic analysis. Bigger samples were used to test the abrasive wear resistance on the abrasive cloth.

The hardness of the samples was measured using the Vickers method with an HPO 250 AQ device (Aquastyl Slovakia Ltd., Považská Bystrica, Slovak Republic) under a load of 98.1 N (HV 10). The hardness measurement on the test specimens was performed in sections perpendicular to the remelted layer (vertical sections) in two ways.

In the first one, the hardness in the remelted layer was measured at a distance of 0.5 mm from its surface (measurements x_i in Figure 1). Based on the hardness values obtained, the uniformity of the remelting conditions (technology parameters) on the sample surface was evaluated.

The second way of the hardness measurement evaluates the sample substrate as well in the direction of its longitudinal axis (measurements y_i in Figure 1). The hardness values obtained were used to determine the depth of remelting or the heat-affected zone formed during remelting. The abrasion resistance of the remelted layers was determined using a device for testing the relative abrasion resistance of the materials on an abrasive cloth (pin-on-disc) at ambient temperature. The scheme of the device is shown in Figure 2. An abrasive cloth (corundum twill with a grain size of 120) with a circle shape of a diameter of 480 mm

was used in the test. The motion path in the test forms a spiral from the edge of the sanding sheet towards its centre so that the tested sample surface was always in contact with the unused cloth. The length of the friction path was 50 m, and the load used was $0.32 \text{ N}\cdot\text{mm}^{-2}$. The wear resistance measure was the weight loss of the test specimen. The weight of the test specimens before and after the abrasive wear test was measured using a Precisa 205A balance (Precisa Gravimetrics A. G., Dietikon, Switzerland) with an accuracy of 0.0001 g.

The samples for the abrasive wear resistance test on the abrasive cloth were cylinders with a diameter of $\varnothing 10 \text{ mm}$ and a height of 20 mm. From the bigger part of the remelted sample, one sample was taken for the abrasive wear resistance test on an abrasive cloth, and five weight loss measurements were performed. The sample was produced by turning, with cutting conditions not causing thermal changes. The remelted side of the sample was ground horizontally so that the sample was in complete contact with the abrasive cloth. Standard samples from non-remelted steels were produced in the same way. The microstructure of remelted layers was characterised using a scanning electron microscope (SEM) Tescan Vega-3 LMU (TESCAN Ltd., Brno, Czech Republic) with a dispersive energy X-ray (EDX) spectrometer Bruker XFlash Detector 410-M (Bruker Nano GmbH, Berlin, Germany). Surfaces after wear resistance tests were examined and evaluated by SEM.

3 Results And Discussion

3.1. Microstructure and Chemical Composition of Remelted Layers

By TIG arc remelting of the samples with the Pulnierpulver nitriding powder on their surfaces, a remelted layers with a significantly different microstructures were formed on the surfaces of the samples of the tested steels compared to the samples that were not remelted. The differences in the microstructure of the remelted layers on particular steel grades (Figure 3a-c) are distinct. They can be attributed to the influence of the respective alloying elements.

The remelted layer on the 25CrMo4 sample (Figure 3a, detailed in Figure 4a) has a dendritic matrix formed by fine martensite and residual austenite, in which large martensite needles are deposited. The microstructures of the remelted layers were etched selectively to avoid over-etching of the interdendritic regions. Such resulting microstructure has been created by the primary formation of a dendritic structure formed by austenite, which subsequently transformed into martensite and residual austenite in the subsolid region by further cooling. The presence of martensite in dendrites has been described in [38-41]. The largest hardening was achieved on the surface of this sample. Needle-shaped martensitic formations are present to a depth of approximately 1 mm from the sample surface. It can be attributed to the positive influence of Cr and Mo on hardenability. EDX analysis (Figure 5) showed the presence of Cr and Mo in the remelted layer. The remelted area was also enriched with N, with the highest N content of all used steels.

The microstructure of the remelted region of the 30CrMoV9 sample has a dendritic character (Figure 3b, detail in Figure 4b), with the martensite needles concentrated locally only in the upper part of the remelted

layer. The homogeneity of the remelted area is disturbed by cracks formed during solidification after remelting, resulting likely from a local toughness decrease of the remelted layer in the regions with martensite formed. The cracks in the 30CrMoV9 sample are mainly due to the higher Cr content in the remelted layer (it follows from the EDX analysis in Figure 6) [42]. The content is almost twice the values of Cr content in the other two samples examined. The higher Cr content, with the content of V (not present in other used steels) and N, could cause a reduction of the remelted layer resistance to crack generation. Such a significant toughness reduction leading to crack generation was only local (in two positions shown in Figure 3b). The results of the EDX analysis confirm the presence of Cr and N in the remelted layer, even directly in the martensite (Figure 6), but the presence of V and Mo in the subsurface part of the remelted layer was not confirmed. It is the local absence of V and Mo at the measurement site (area of large needle-like formations). The presence of V and Mo was not detected in all measurements in the subsurface area of the remelted layer with needle-like formations and inside the dendrites (segregation of these elements). V and Mo were demonstrated only in the interdendritic regions).

The matrix of the remelted layer of the 41CrAlMo7 sample is also dendritic, formed by fine martensite and residual austenite, with relatively massive martensite needles segregated continuously to a depth of approximately 0.1 mm below the surface (Figure 3c). The results of the EDX analysis (Figure 8) showed the presence of Cr and N in the remelted region. The presence of Al and Mo in the remelted layer was also confirmed, but only in trace amounts without the potentiality of influencing its final properties.

The differences in the N contents in the particular remelted layers are not marked. The effect of Cr on the solubility of N in Fe is significant at higher Cr contents (above 10 %) [43]. At low Cr contents, being our case, the effect of Cr on N solubility may not be significant. The positive effect of alloying nitride-forming elements (Cr, Al, V) on increasing the N solubility in Fe can also be reduced by the C content, which has an adverse effect on the solubility of N in Fe [44-45]. Disproportions in terms of comparing the Cr and N content in the remelted layers can also be caused by kinetic factors in the time of remelted layer cooling and the non-equilibrium conditions of the surface remelting process.

3.2. Hardness in Remelted Layers

The average hardness values HV 10 found at the measuring points x_i in Figure 1 for test specimens without remelting, with remelting in argon 4.6 and with remelting of Pulnierpulver nitriding powder are shown in Figure. 9. The results show that the base hardness (non-remelted steels) was approximately the same for all the steels examined (the difference in values does not exceed 8 %). The measured values of the hardness of particular steels in the non-treated state correspond to the content of C and alloying elements in them.

The remelting in the shielding atmosphere of argon 4.6 alone caused an increase in the average hardness of all the steels examined. The most significant increase in hardness value was found for the 25CrMo4 sample by 246 HV 10 (i.e., by 155.9 %). Samples 30CrMoV9 and 41CrAlMo7 reached almost the same hardness values even after remelting in a shielding atmosphere of argon 4.6 (the difference was only 4

HV 10, i.e., 2.3 %), with the hardness growth by about 120 %. The most significant increase in hardness of 25CrMo4 steel was likely due to the higher N content in the remelted layer, which resulted in a higher level of strengthening (oversaturation) of the solid solution. The influence of Cr and other alloying elements did not significantly affect the hardness value. After remelting the investigated steels in the presence of nitriding powder, a significant increase in average hardness was achieved compared to steels remelted in a shielding atmosphere of argon 4.6. The highest increase was recorded for the 25CrMo4 sample by 502 HV 10 (i.e., by 124.1 %). This increase can be attributed mainly to the enrichment the remelted layer with nitrogen. The nitrogen in the remelted layer contributed to a significant strengthening of martensite in particular, as evidenced by the significantly higher hardness values obtained after remelting the nitriding powder compared to the values after remelting without its presence (Figure 9). Compared to the state without remelting, the sample 25CrMo4 reached the highest increase in average hardness after remelting in the presence of nitriding powder by 748 HV 10 (i.e., by 473.5 %). Such significant increases in hardness of the investigated steels are caused by an increase in hardenability caused by enriching the matrix with nitrogen. Figure 10 shows the dependence of the average values of the hardness HV10 on the average values of the nitrogen content in the remelted layers. There were five measurements performed in each remelted layer. The dependence of hardness on the nitrogen content can be expressed by the equation with the coefficient of determination $R^2 = 0.995$:

$$HV = 445.02 \cdot c_N - 217.24$$

where:

HV – hardness HV 10,

c_N – carbon content (wt %).

The austenite formed by the cooling of the remelted layer contained nitrogen at interstitial positions. Upon transformation of nitrogen-enriched austenite to martensite, nitrogen entered the martensite structure. Since nitrogen was added to the system (from nitriding powder), it can be considered an alloying element. Nitrogen causes the solid solution to strengthen approximately twice as much as carbon [46].

A graphical representation of the course of hardness as a function of the distance from the surface of the sample obtained from the measurements at the measuring points y_i of Figure 1 is shown in Figure 11. The highest hardness values were found on a 25CrMo4 sample, with the highest value reaching 936 HV 10. The increased hardness (above 800 HV 10) was measured to a depth of approximately 1.5 mm, the thickness of the layer with hardness above 900 HV10 corresponding to the layer in which they are present needle-like formations (Figure 3a and 4a, respectively). In the heat-affected zone, there was a relatively sharp decrease in hardness to the level of 326 HV 10 at a depth of 2 mm, while the decrease in hardness to the level of hardness of the base material (165 HV 10) was achieved at a depth of 2.5 mm.

Sample 30CrMoV9 showed a similar hardness profile as sample 25CrMo4, which was characterised by a relatively stable level of hardness to a depth of 1 mm (with a maximum value of 770 HV 10), a slight decrease to a depth of 1.5 mm to 605 HV 10 and a subsequent significant decrease in the heat affected area to the hardness level of the base material (169 HV 10).

The 41CrAlMo7 sample retained increased hardness (exceeding 650 HV10) to a depth of 1.5 mm. The hardness profiles in Figure 11 also show that the reinforcing effect of Mo (in interaction with the higher N content) alone was significantly higher than in the case of its combination with nitride-forming elements Al, resp. V. A more significant strengthening effect of V (in interaction with the higher Cr content) than Al is also visible. The influence of Cr alone on strengthening showed to be less significant.

The lower hardness values of the 30CrMoV9 and 41CrAlMo7 samples (Figure 11) in the remelted layers can be attributed to the fact that no needle-like shapes were present in the measured parts of the remelted layers, in contrast to the 25CrMo4 sample. Only a nitrogen-strengthened dendritic structure was found in these areas. In all cases, we noticed a significant decrease in hardness in the heat-affected zone because the strengthening effect of nitrogen was no longer applied here.

3.3. Abrasive Wear Resistance of Remelted Layers

All examined samples were tested on an abrasive cloth. The degree of abrasion resistance was the average weight loss of the samples achieved by a defined abrasive wear process. The values of the average weight losses of the examined samples are shown in Figure 12. The highest values of average weight losses were achieved in samples of investigated steels without remelting. These values can be taken as a basis for comparing the wear resistance obtained by TIG remelting. The lowest weight loss value was measured in the sample 30CrMoV9 (0.2037 g), which represents a difference of 7.9 % compared to the sample with the highest weight loss (25CrMo4). While the hardness values of the investigated steels without remelting were almost the same (Figure 9) regardless of their chemical composition, the values of the average weight losses show in particular the influence of the Cr content on the abrasion wear resistance. By remelting in a protective atmosphere of argon 4.6, the average weight losses (wear intensity) of all investigated steels decreased. In this case, the lowest weight loss of the sample was 25CrMo4 (0.1669 g), while the weight loss was reduced by 24.1% compared to the no remelting state. The difference between the highest and lowest value of the average weight losses of the samples remelted in the protective atmosphere argon 4.6 was 10.4 %. Significantly the lowest values of average weight losses were achieved by samples of all investigated steels remelted in the presence of nitriding powder. Best resistance to abrasive wear, i. e. the lowest weight loss in the state after remelting in the presence of nitriding powder, was found in the sample 25CrMo4 (0.1131 g), with a decrease in wear intensity of 48.5 % compared to the state without remelting (which is also the most significant percentage decrease in wear intensity of all steels examined) and 32.2 % compared to the state after remelting in a protective atmosphere argon 4.6.

The influence of the content of individual alloying elements is qualitatively similar to that of remelting in a protective atmosphere of argon 4.6. However, this effect is significantly amplified by doping the

microstructure with nitrogen. The obtained results show that the changes in the microstructure of steel after remelting nitriding powder (Chapter 3.1) significantly increase the resistance to abrasive wear. The performed microstructural analyses indicate that the nitrogen-saturated matrix influences the abrasive wear resistance increase. This statement is confirmed by the fact that hardness and wear resistance values were significantly lower when remelted without the nitriding powder (only in the protective atmosphere of argon 4.6). EDX demonstrated the presence of N in the layers remelted in the presence of nitriding powder, from which we conclude that the use of the nitriding powder enriched the structure of the remelted layer by N (in all three investigated cases). The hardness values obtained indicate that the microstructure of the remelted layers is formed by martensite.

3.4. Mechanism of Abrasive Wear

The wear mechanisms of the remelted layers were analysed by SEM photographs of the worn surfaces of the examined samples. The worn surface of the 25CrMo4 sample showed a relatively high uniformity of wear and a regular (rectilinear) shape of the abrasive grooves (Figure 13a), which were mainly caused by the micro milling process. The micro-scoring mechanism was used only to a limited extent. Microplastic deformation is not present at all. It was probably due to the presence of nitrogen hardened high hardness martensite in the remelted layer of the 25CrMo4 sample. Samples of 30CrMoV9 and 41CrAlMo7 showed a very similar character to worn surfaces (Figure 13b, c), on which areas with a predominant creasing mechanism were visible, with the presence of unusual formations on both worn surfaces. In both cases, it was probably an abrasive particle trapped in a worn surface with local plastic deformation of its surroundings.

3.5. Evaluation of Objectives Achievement

The main result of the presented research is the verification of the process of layers with increased hardness and abrasive wear resistance forming by steel surface TIG remelting with powders of suitable chemical composition. This work builds on previous research with the same procedure used to create remelted layers containing carboborides. The microstructure of the remelted layers containing carboborides gained a significant hardness and wear resistance increase.

Based on that, we assumed the formation of hard nitrogen-based structures during remelting with the nitriding powder. The process resulted in remelted layers with a matrix significantly enriched in nitrogen. This enrichment was uniform throughout the remelted layer volume. The presence of nitrogen in the matrices of all remelted layers caused a significant hardness increase (five times on average) and abrasion resistance increase (almost twice) compared to not remelted steels. The effect of nitrogen on the increase in hardness and abrasive wear resistance appears to be significant, as evidenced by significantly higher values of the tested properties compared to the values obtained when remelting samples in a protective argon atmosphere.

However, the conditions for forming hard nitrogen-based phases could not be met. It was probably due to the kinetic parameters (high cooling rate not allowing precipitation processes to occur) and the

nonequilibrium conditions of the remelting process. In the future, we would like to focus on the kinetic parameters control of the remelted layers cooling to achieve the formation of hard nitrogen-based phases.

The contribution of the paper lies in the demonstration of the possibility of using TIG remelting as a simple, cheap, and technologically accessible method for layers with improved hardness and abrasive wear resistance production. Based on the experiments performed, it is possible to improve this method in the future and achieve an industrial application.

4 Conclusions

The influence of remelting of selected steels by TIG process in the presence of increased amounts of nitrogen in the form of nitriding powder on their hardness and resistance to abrasive wear was investigated. The following findings lead to the following results:

1. In the layers remelted in the presence of nitriding powder, the presence of nitrogen was confirmed in all investigated steels, but its concentration was not sufficient to form hard nitrides, or carbonitrides. However, the detected nitrogen concentration in the remelted layers was sufficient to saturate the matrix, which caused a significant increase in its hardenability, i.e. the formation of martensite during cooling of the remelted layer, as well as the alloying of a metal matrix with nitrogen.
2. In the layers remelted in the presence of nitriding powder, all investigated steels showed a significant increase in hardness (4.4–5.7 times) and abrasion resistance (1.8–1.9 times) compared to steels without remelting, which can be attributed to the presence of nitrogen-saturated martensite in the microstructure of the remelted layer.
3. In all investigated steels, a significant increase in hardness and wear resistance was achieved due to the remelting of the nitriding powder compared to the state with remelting in the protective atmosphere of argon 4.6, which results in a significant effect of N on increasing the hardenability of the remelted layer and strengthening of the matrix.
4. By remelting in the presence of nitriding powder, it is possible to achieve layer thicknesses of up to 1.5 mm with a relatively stable value of increased hardness to the level of 600–900 HV 10 in a very short time of exposure to elevated temperature.
5. TIG remelting of powders with a suitable chemical composition makes it possible to achieve a significant increase in hardness and wear resistance in remelted layers without the need for further heat treatment, the resulting layers reaching a thickness of more than 1 mm.

The obtained results of the performed experiments confirmed the correctness of the assumptions mentioned above. After surface TIG remelting of the CaCN_2 -based nitriding powder, the remelted layer was enriched by N to a relatively large distance from the surface of the samples. The presence of nitrogen had a positive effect on the increase in hardenability of all steels examined, which led to a significant increase in hardness and resistance to abrasive wear. The effect of nitrogen on the increase in the investigated properties is documented by a comparison of samples remelted in the absence and

presence of nitriding powder. Thus, it is a new, original experiment which proved the possibility of forming abrasive wear-resistant layers using TIG surface remelting of powders containing certain elements. This method represents a cheap, technologically available, and fast way of forming surface layers with increased hardness and wear resistance, which makes it applicable in engineering, agriculture, earthworks, etc.

Declarations

Acknowledgement

This work was supported by KEGA, grant number 063TUKE-4/2021 and by VEGA, grant number 1/0236/21. The authors also would like to thank Dr. Ladislav Falat (Institute of Materials Research, Slovak Academy of Sciences, Košice, Slovakia) for help in performing microstructural and EDX analyses.

Conflict of interest

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Authors' contribution

Ivan Kováč: conceptualization, experimental plan, initial experiments. Rastislav Mikuš: experiment performing, manuscript writing. Jozef Žarnovský: material preparation, editing. Róbert Drlička: material preparation, data analysis. Marta Harničárová: manuscript writing, data analysis. Jan Valíček: conceptualization, supervision. Milan Kadnár: data curation and project administration. All authors read and approved the final manuscript.

Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Tables

Table 1 Type and chemical composition of tested steels.

Steel grade	Chemical composition (wt%)								
	C	Mn	Si	Cr	Al	V	Mo	P	S
25CrMo4	0.22– 0.29	0.60 – 0.90	max. 0.4	0.90– 1.12	-	-	0.15– 0.30	max. 0.035	max. 0.035
30CrMoV9	0.26– 0.34	0.40– 0.70	max. 0.4	2.30– 2.70	-	0.10– 0.20	0.15– 0.25	max. 0.035	max. 0.035
41CrAlMo7	0.38– 0.45	0.40– 0.70	max. 0.4	1.50– 1.80	0.80– 1.20	-	0.20– 0.35	max. 0.035	max. 0.035

Figures

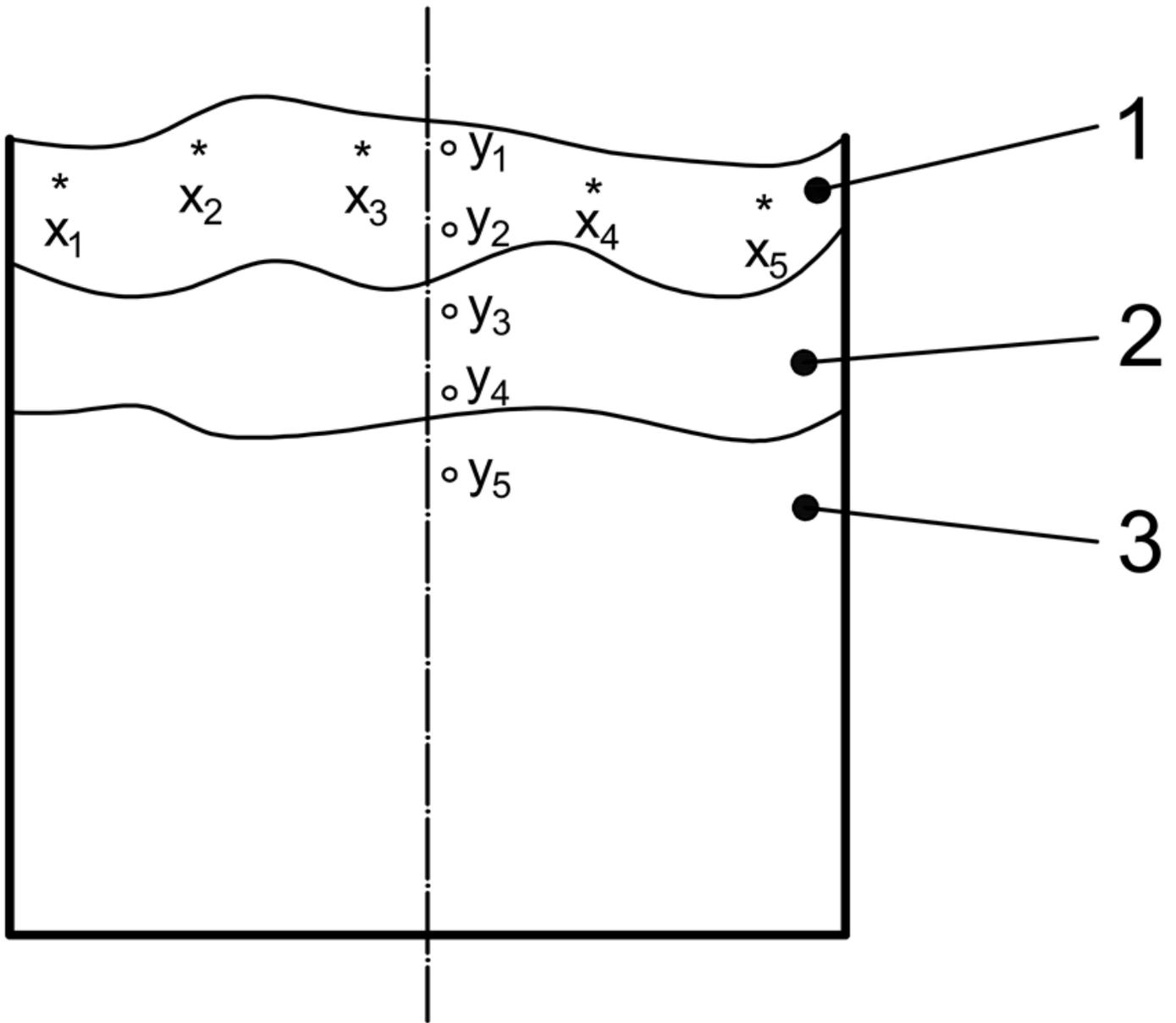


Figure 1

Hardness measurement points in the vertical section of the remelted sample (1 - remelted area, 2 - heat affected area, 3 - base material).

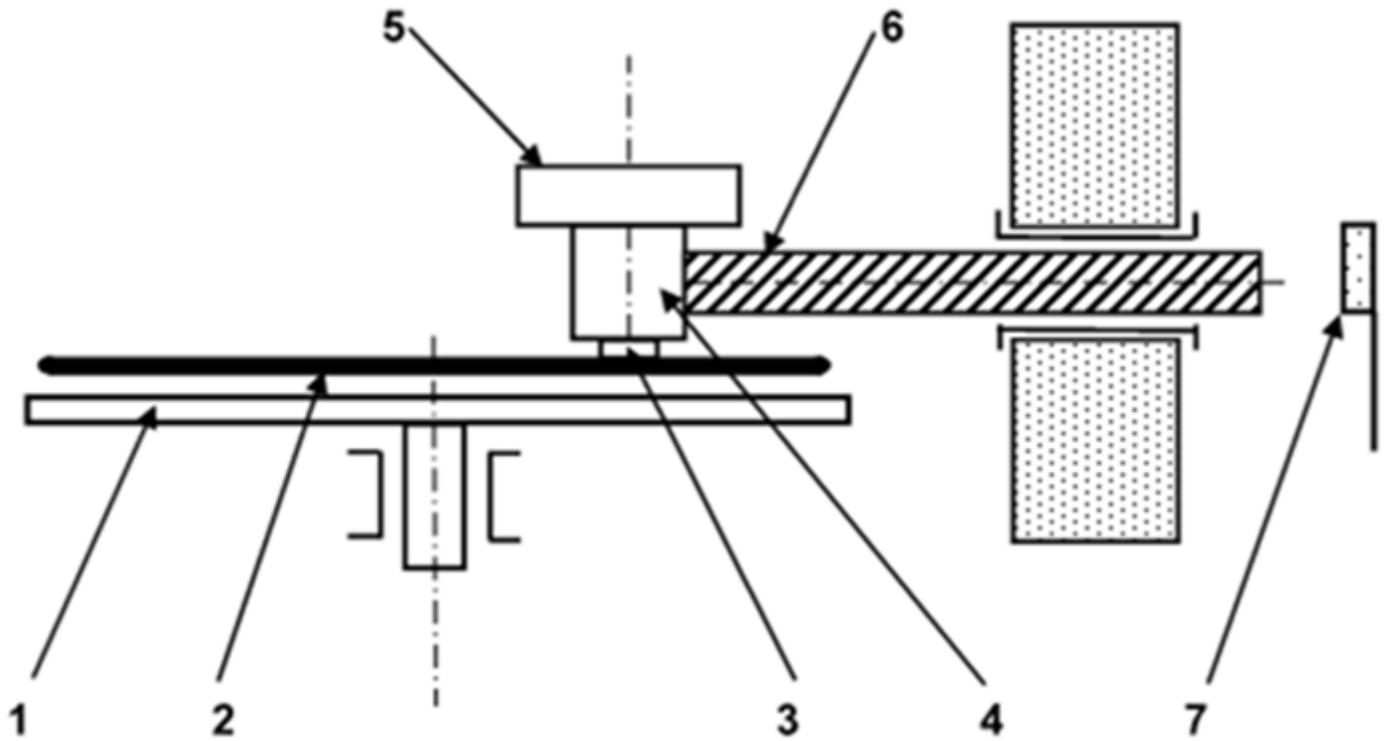


Figure 2

Schematic of equipment for testing the resistance of materials to abrasive wear on an abrasive cloth (1- rotating round plate, 2 - abrasive cloth, 3 - test specimen, 4 - holder, 5 - weight, 6 - movement screw enabling transverse movement of the specimen, 7 - limit switch).



Figure 3

Microstructure of remelted layer of steels in vertical cross-section: (a) 25CrMo4; (b) 30CrMoV9; (c) 41CrAlMo7.

Figure 4

Comparison of acicular martensitic structure formed in remelted steel layers: (a) 25CrMo4; (b) 30CrMoV9.

Figure 5

EDX analysis of remelted layer of the sample 25CrMo4.

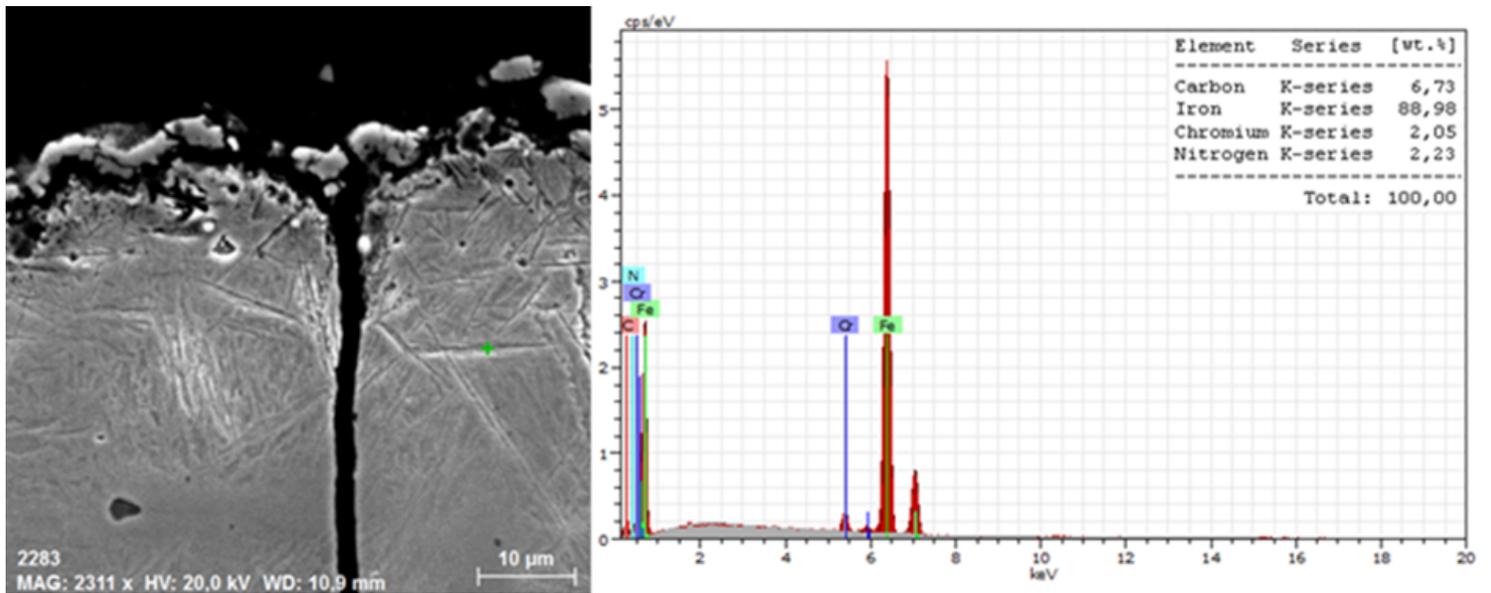


Figure 6

EDX analysis of remelted layer of the sample 30CrMoV9.

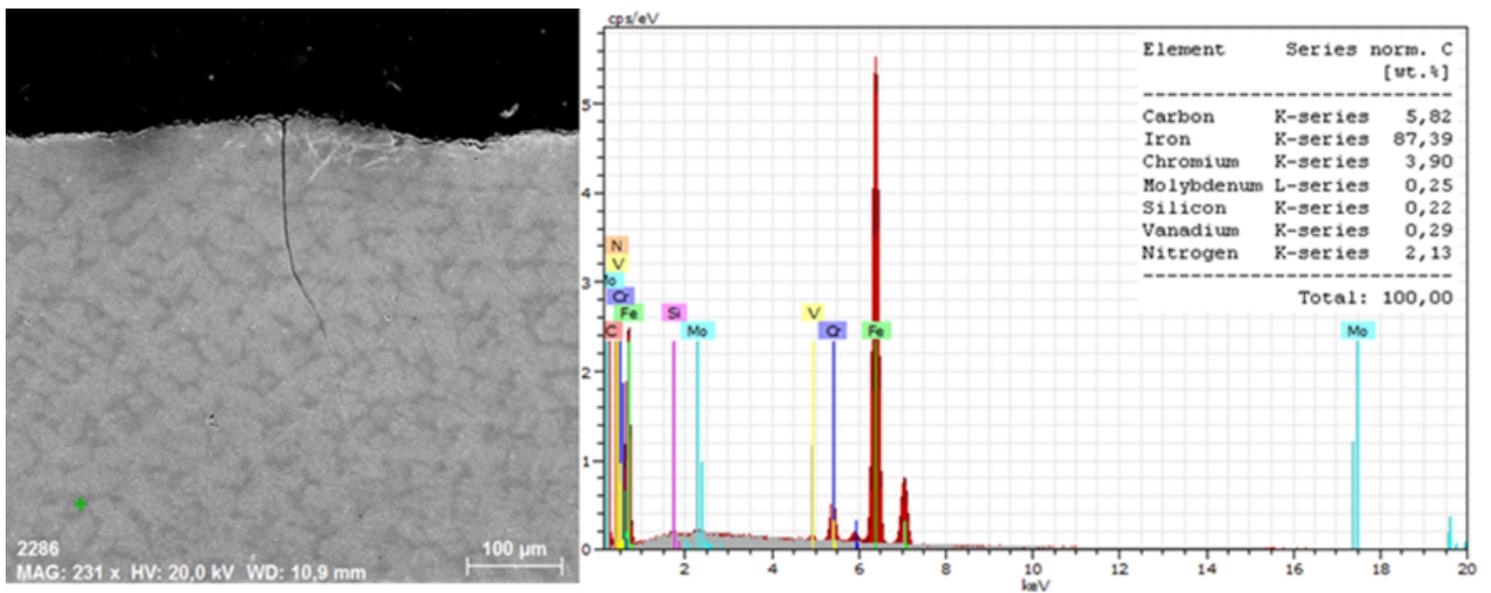


Figure 7

EDX analysis of interdendritic region in a remelted layer of the sample 30CrMoV9.

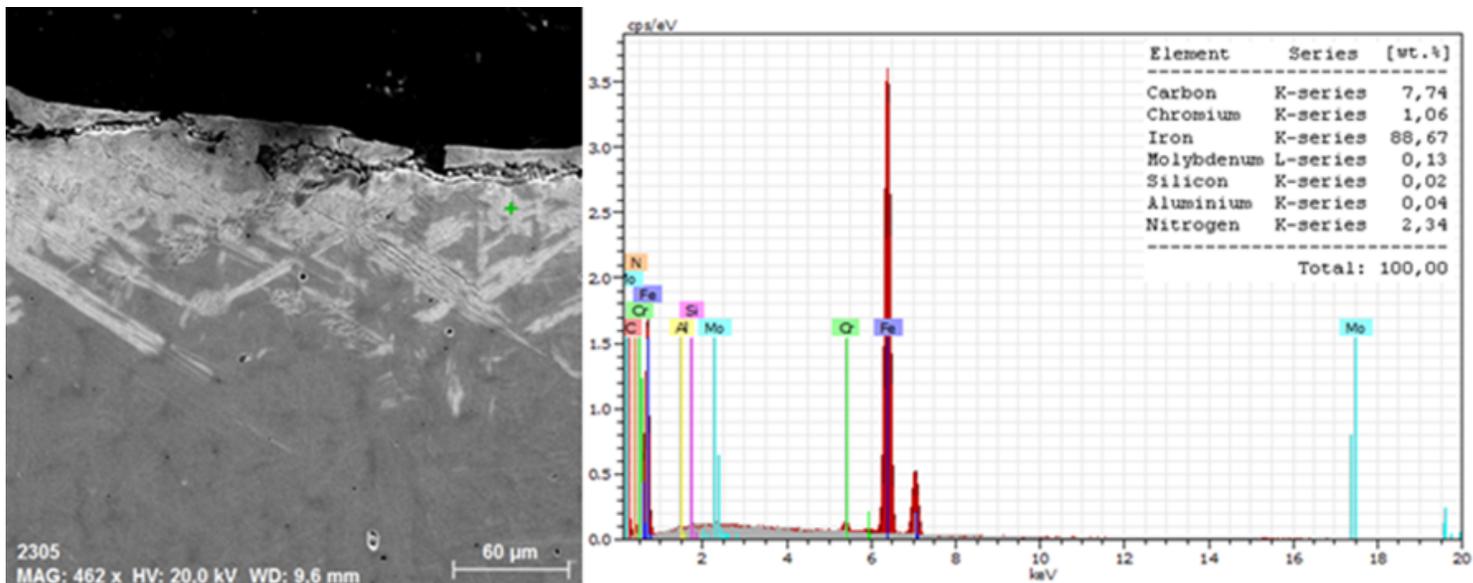


Figure 8

EDX analysis of remelted layer of the sample 41CrAlMo7.

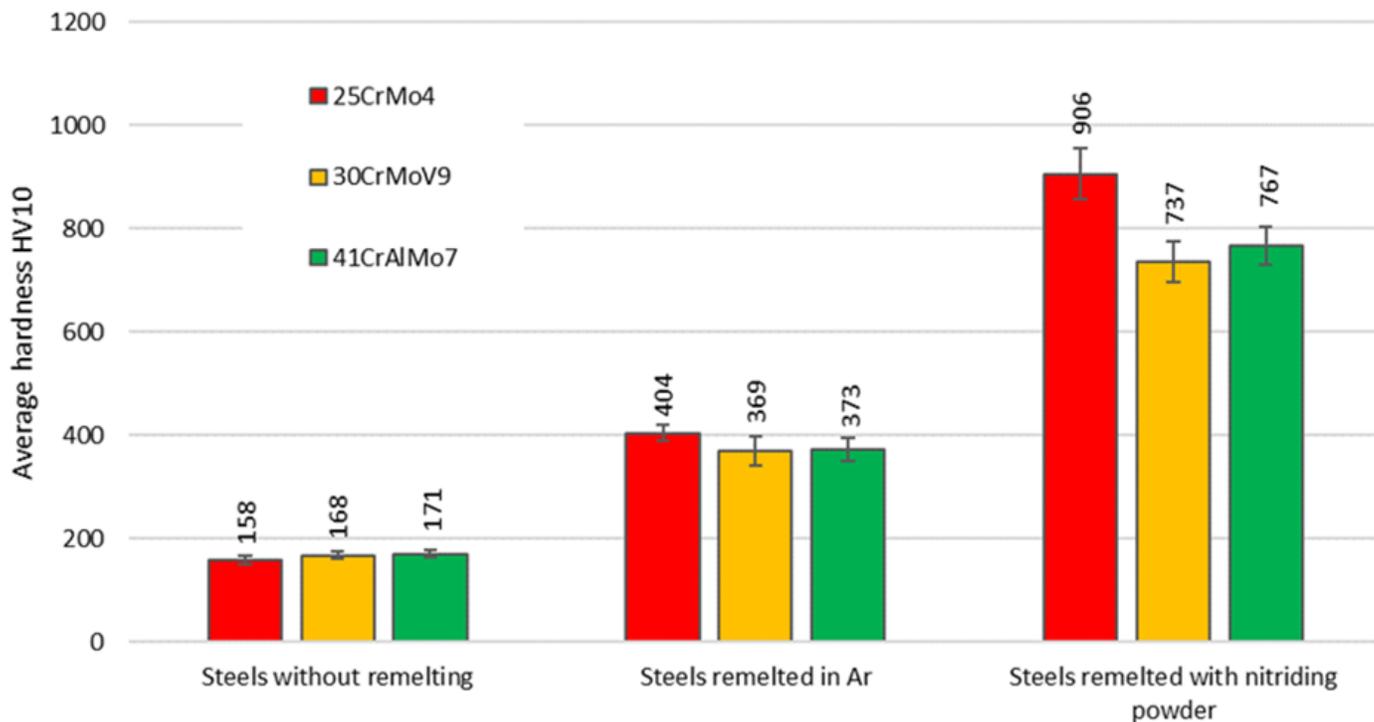


Figure 9

Average values of HV 10 hardness of examined samples.

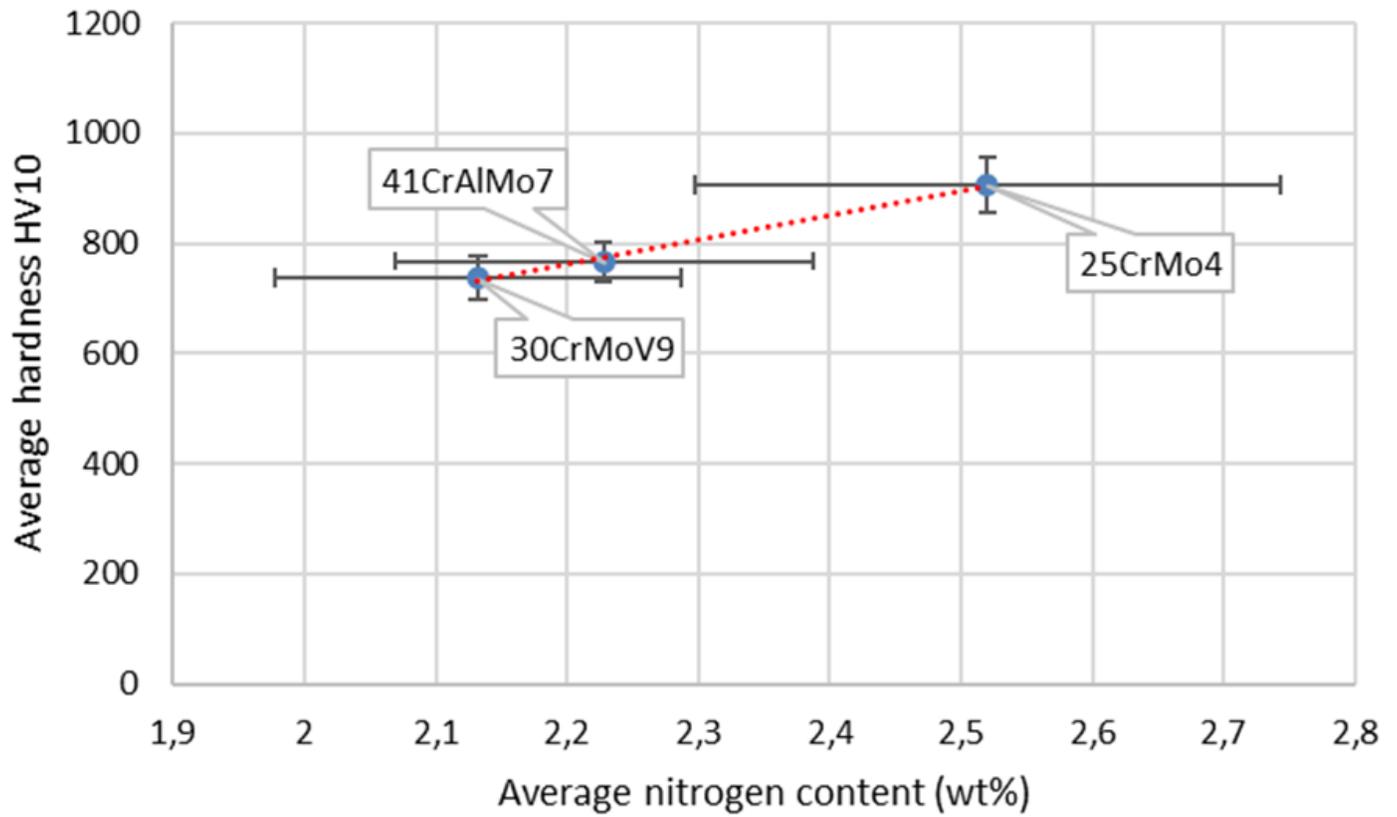


Figure 10

Dependence of average hardness HV 10 on average nitrogen content in remelted layers.

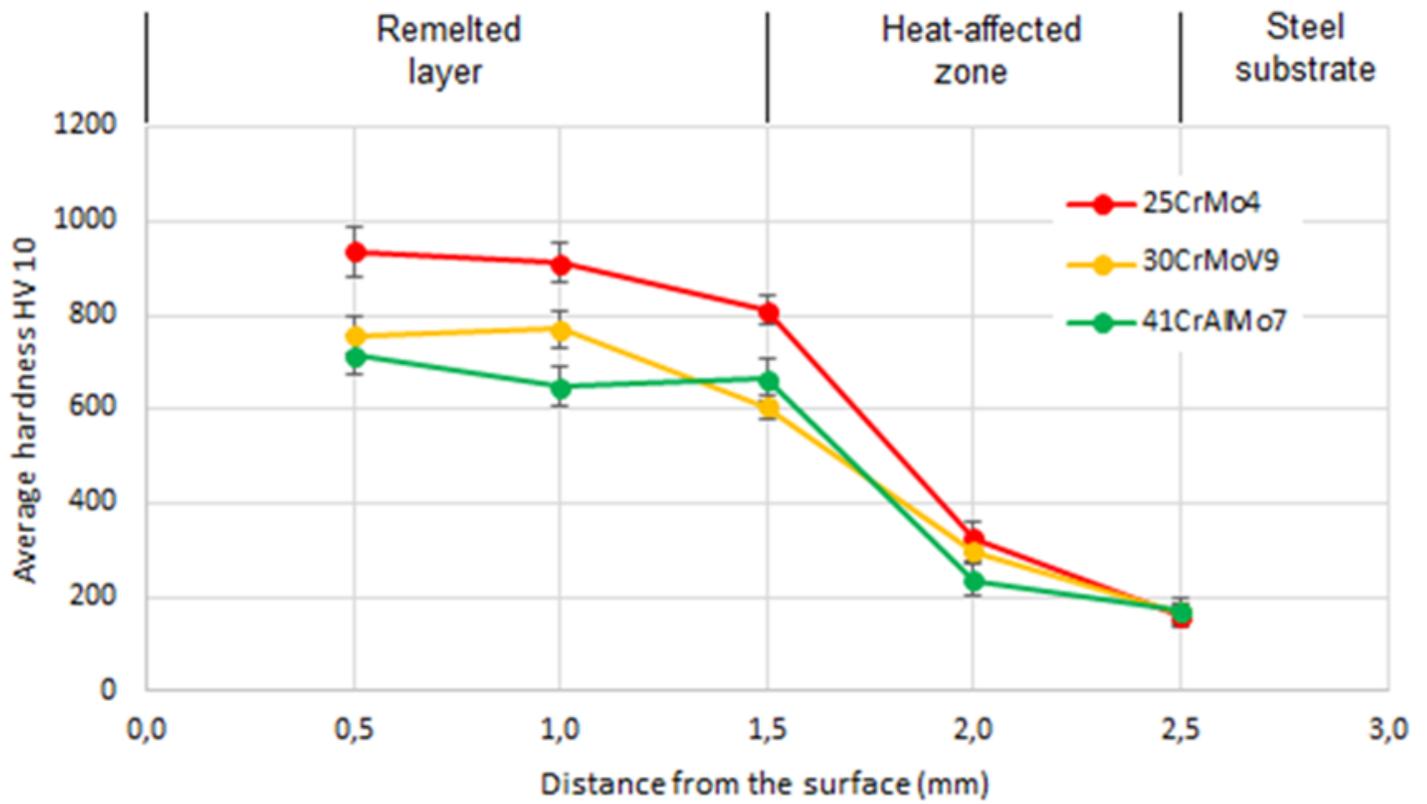


Figure 11

The course of HV 10 hardness in the investigated steels after remelting in the presence of nitriding powder depends on the distance from the sample surface.

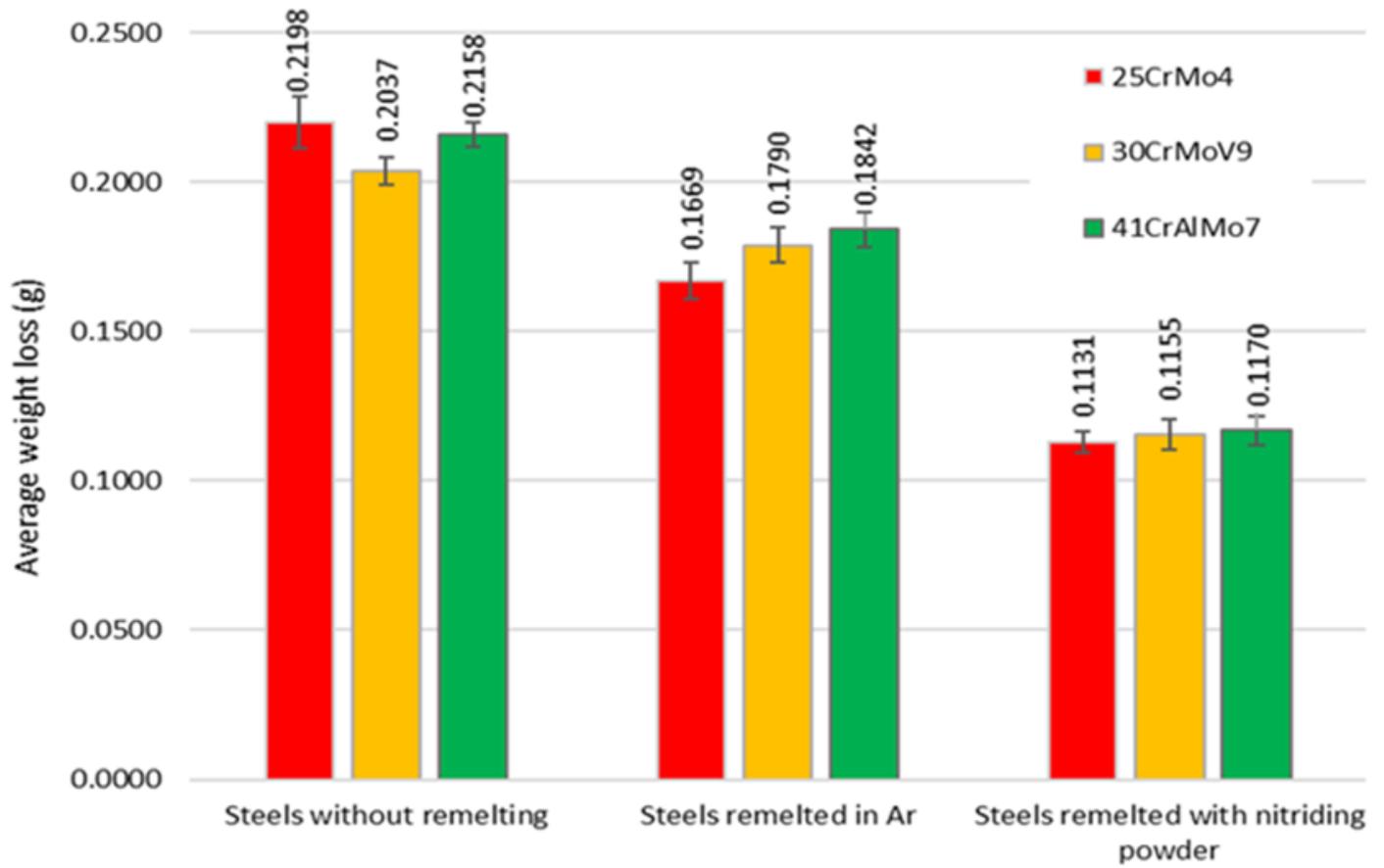


Figure 12

Average weight losses of the examined samples.

Figure 13

Worn surfaces of remelted steel layers: (a) 25CrMo4; (b) 30CrMoV9; (c) 41CrAlMo7.