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CREATING WEAR-RESISTANT LAYERS ON 41CrAlMo7 STEEL USING TIG SURFACE REMELTING

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The article deals with the process of surface remelting of steel 41CrAlMo7 by electric arc (TIG) in the presence of powders with a defined chemical composition. Commercially available powders Pulnierpulver based on calcium cyanamide (CaCN₂) (source of nitrogen) and Durborit G based on boron carbide B₄C (source of boron) were remelted. The effect of remelting on the change of microstructure in the remelted area was examined to achieve an increase in hardness and resistance to abrasive wear. The measurements of the hardness of HV 1 were carried out, as well as determination of resistance to abrasive wear on the abrasive cloth with Al₂O₃ particles. The microstructures of remelted layers were observed by LOM and details by SEM. By remelting the examined steel, a significant increase in hardness and resistance to abrasive wear was achieved to a depth of up to 1.5 mm from the surface. An almost four times increase in hardness and an almost two times increase in wear resistance was found when remelting the Pulnierpulver powder, or more than three times increase in hardness and more than 1.5 times increase in resistance to abrasive wear when remelting the Durborit G powder compared to steel without remelting. The presented procedure of TIG surface remelting of powders containing a certain element represents a cheap, accessible, and fast way of creating surface layers with increased hardness and wear resistance. The method is applicable for increasing the wear resistance of functional parts of machines for agriculture, earthmoving, etc.

Keywords: TIG remelting; nitrogen reached layers; boron reached layers; hardness; abrasive wear resistance

Abrasive wear can be defined as the loss of material caused by protrusions of the surface of another material or particles (bound or free) located in the vicinity of the worn material during their relative movement. The result of the wear process is the dulling of the blades (functional parts) of soil processing tools with a subsequent negative impact on their functionality and the energy intensity of soil processing (Eremeev, 2013; Bialobrzenska and Kostencki, 2015).

Ensuring the highest possible service life of the functional components of agricultural machines can be solved by their appropriate structural, but especially material, solution. Despite several published material solutions for modifying functional parts of tillage machines (Zhang and Kushwaha, 1995; Bhakat et al., 2007; Nalbant and Palali, 2011; Novák et al., 2014; Królicka et al., 2020), this problem is not solved satisfactorily.

For technological and economic reasons, wear-resistant materials are not often used for whole parts, but these materials are applied in the form of layers to the functional surfaces of parts made of less strong and cheaper materials. These layers serve as protection against wear or other degrading effects of the operating environment. In these cases, in addition to the properties and microstructure of the basic materials (usually carbon, low- and medium-alloyed steels), the properties and microstructure of formed layers become important (Müller and Hrabě, 2013; Viňáš et al., 2013; Müller et al., 2018; Votava et al., 2020).

Various methods can be used to create wear-resistant layers (Béjar and Moreno, 2006; Eroglu, 2009; Coronado et al., 2009; Yuan et al., 2017; Ľavodová et al., 2018; Šmak et al., 2023). In addition to conventional methods based on the creation of wear-resistant layers using additional materials by melting technologies (Buchanan et al., 2007; Kotus et al., 2011; Brezinová et al., 2016; Arsić et al., 2022; Kangalov et al., 2022; Votava et al., 2022), it is possible to use methods based on the remelting of materials in environments with a suitable chemical composition (Bourithis et al., 2002).

The article presents the results of remelting of 41CrAlMo7 steel by electric arc (TIG) in environments rich in nitrogen or boron to enrich the remelted areas with these elements. This should create conditions for the formation of microstructures with increased hardness and wear resistance. Steel was used as a basic material for remelting, which, based on its chemical composition, is expected to achieve a strengthening effect after enrichment with nitrogen or boron.

The presented experiment assumed that by means of an electric arc it is possible to achieve a condition allowing the initiation and progression of diffusion processes in the surface layer of remelted steel leading to the enrichment of the remelted layer with nitrogen or boron.

The work builds on previous research by the authors, in which the method of surface remelting of steels by electric arc in the presence of nitrogen or boron was applied (Kováč et al., 2014; Kováč et al., 2022).

Material and methods

Researched materials

Medium-alloyed steel 41CrAlMo7 was used as the basic material, the chemical composition of which makes it possible to achieve relatively high hardenability. The chemical composition of the examined steel is given in Table 1.

The nitriding powder Pulnierpulver with calcium cyanamide (CaCN_2) as the main component was used as the nitrogen source. The boriding powder Durborit G was used as the boron source; its main component was boron carbide (B_4C). The company AZ Prokal s. r. o. Brno (Czech Republic) is the supplier of both powders.

Preparation of samples by remelting

The process of saturating the surface of the examined steel was realized by remelting the powders (mentioned in the chapter Researched materials) by means of an electric arc. The powders were applied to the metallic clean surface of the remelted samples. The thicknesses of the applied powder layers were approximately 1 mm. Before application, the powders were moistened with distilled water to achieve a pasty consistency. Subsequently, the samples were heated in an oven at a temperature of 50 °C for 20 minutes. This created solid layers of powders, which prevented them from being blown away by the shielding gas during remelting. The remelted samples of the examined steel had a circular cross-section with a diameter of $\varnothing$ 20 mm and a height of 20 mm. The entire cross-sectional area of the sample was remelted.

The remelting of 41CrAlMo7 steel was realized by welding technology with a non-melting tungsten electrode in an inert shielding gas atmosphere (TIG). A welding inverter SMARTY TX 160 Alu (Air Liquide Slovakia s. r. o., Nitra, Slovakia) was used as a heat source during remelting. The remelting process took place with a welding current of 110 A, in a shielding gas atmosphere of 100% Ar at a gas flow rate of 10 l·min⁻¹. Remelting was carried out by manual movement of the torch, so the speed of movement of the torch cannot be precisely determined.

In addition to the remelting of samples with layers of examined powders, the samples of the examined steel without the presence of any powder were also remelted only in a shielding gas atmosphere of 100% Ar. This made it possible to assess the achievement of required changes in the chemical composition of surface layers of the examined steel after remelting the examined powders. Samples without remelting were used as a starting point for comparing the achieved effects. The properties of all created samples were determined by the same methods. Three samples were created for each remelting variant examined (remelting in Ar, Pulnierpulver remelting, Durborit G remelting).

Research methods

The remelted samples were cut into two equal parts with a cutting disc perpendicular to the remelted layer. One part of the samples was used for hardness determination and metallographic analysis. The second part of the samples was used to prepare samples for the test of resistance to abrasive wear on the abrasive cloth. When cutting the samples, conditions were ensured that prevented them from being affected by heat.

Determination of hardness

The hardness of the samples was determined in two ways. The first method was to determine the hardness in the remelted layer at a distance of 0.5 mm from its surface (measurement x_i in Fig. 1). From obtained hardness values, it was possible to evaluate the uniformity of achieving the required remelting conditions on the surface of the sample. In this way, the hardness of the examined steel was also determined without remelting, as well as with remelting in a protective argon atmosphere (without the presence of powders). Determined hardness values were used to compare the achieved benefits of powder remelting (standards).

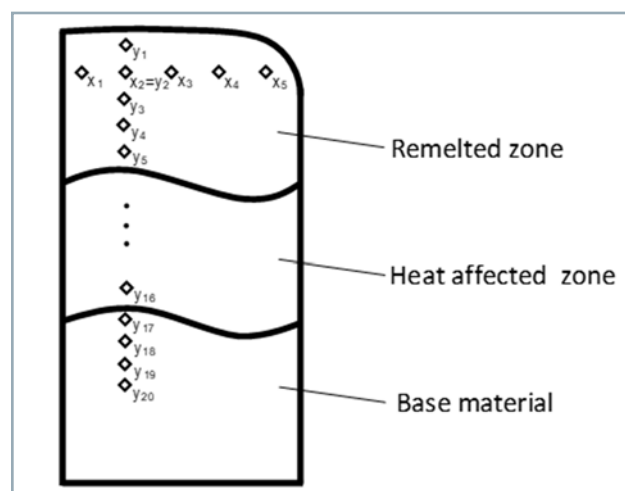


Fig. 1 Hardness measurement points in the vertical cross-section of the remelted sample

The second method was to measure the hardness towards the inside of the material in the direction of the longitudinal axis of the sample (measurement y_i in Fig. 1). The hardness values obtained in this way were used to determine the depth of remelting, or the width of the heat-affected area created during remelting.

Both methods used the standard Vickers method of determining hardness under a load of 9.8 N (HV 1) and at normal temperature. Hardness tests were performed with the device FM-100 (Future-tech Corp., Kawasaki, Japan).

Table 1 Chemical composition of steel 41CrAlMo7

Component	C	Mn	Si	Cr	Al	Mo	P	S
Wt. %	0.35–0.42	0.30–0.60	0.17–0.37	1.35–1.65	0.70–1.10	0.15–0.25	max. 0.035	max. 0.035

Determination of resistance to abrasive wear

The resistance of remelted layers to abrasive wear was determined on a device for testing the relative resistance of materials to abrasive wear on an abrasive cloth (pin-on-disc) at ambient temperature (Fig. 2).

An abrasive cloth (corundum twill with grain size 120) in the shape of a circle with a diameter of 480 mm was used during the test; it was attached to the driven disc of the device. The movement of the test body loaded with a weight along the abrasive cloth followed a spiral from the edge of the abrasive cloth towards its centre so that the contact surface of the sample was always in contact with the unused abrasive cloth. The length of the friction track was 50 m, and the speed of movement of the test body was $0.5 \text{ m} \cdot \text{s}^{-1}$. A specific load of $0.32 \text{ N} \cdot \text{mm}^{-2}$ was used in the test.

The criterion for evaluating wear resistance was the weight loss value of test samples. The weight of test samples before and after the abrasive wear resistance test on the abrasive cloth was determined using a Precisa 205A weight scale (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 had a circular cross-section with a diameter of $\varnothing 10 \text{ mm}$ and a height of 20 mm. They were made by turning from halves of remelted samples obtained by cutting them longitudinally. The remelted end of the sample was subsequently grinded

horizontally to a plane so that the sample was in full contact with the abrasive cloth throughout the cross-section. In the same way, reference samples were also produced from the examined steel without remelting. The exclusion of thermal influence was ensured in all chip machining procedures. Three samples were produced for each variant examined for resistance to abrasive wear (no remelting, Ar remelting, Pulnierpulver remelting, Durborit G remelting).

From the average values of weight losses of individual variants investigated, the values of relative resistance to abrasive wear Ψ_{abr} were calculated according to the formula:

$$\Psi_{abr} = \frac{\Delta \bar{m}_R}{\Delta \bar{m}} \quad (1)$$

where: $\Delta \bar{m}_R$ – average weight loss of the reference variant – 41CrAlMo7 steel without remelting (g); $\Delta \bar{m}$ – average weight loss of the studied remelting variants (g)

Microscopic analysis

The microstructure of examined samples was evaluated using a light-optical microscope (LOM) Olympus GX51 (Olympus Corp., Tokyo, Japan). The scanning electron microscope (SEM) JEOL JSM-IT300 (JEOL Ltd., Tokyo, Japan) was used for a more detailed microstructure analysis. The preparation of samples for light microscopy was performed using devices and material supplied by Struers (Ballerup, Denmark).

Results and discussion

Hardness

The hardness in remelted layers was determined by two ways. The average values of hardness HV 1 found in the remelted layers of Pulnierpulver and Durborit G powders in the horizontal direction (at points x_i in Fig. 1), as well as in reference samples (steel without remelting and steel remelted only in shielding gas atmosphere Ar) are shown in Fig. 3. The above hardness values show that remelting the steel under test in a shielding gas atmosphere without the presence of any powder caused an increase in hardness of 203 HV 1 (i.e. by 104.6%). Such a significant increase in hardness by simple remelting is due to a comparatively large hardenability of the examined steel, which is determined by its chemical composition (Cr and Mo content).

A much more significant increase in hardness was recorded for samples that were remelted in the presence of powders with a defined chemical composition. After remelting the examined steel in the presence of the Durborit G powder, an increase in hardness of 417 HV 1 (by 214.9%) was achieved compared to the hardness without remelting. Remelting in the presence of Pulnierpulver resulted in an increase in the hardness of 559 HV 1 (by 288.1%). Farayibi et al. (2021) achieved similar hardness values when heat-treating sintered martensitic stainless steel in the presence of nitrogen.

An increase in hardness during remelting achieved by the presence of powders shows a significant influence of the elements contained in the powders (B in the Durborit G powder and N in the Pulnierpulver powder) on the change of microstructure in the remelted layer. The influence of nitrogen is more significant than that of boron.

The courses of average hardness values HV 1 in the vertical direction (at points y_i in Fig. 1), determined on samples remelted in the presence of Pulnierpulver and Durborit G powders, are shown in Fig. 4. From the comparison of hardness courses, it can be concluded that the remelting of

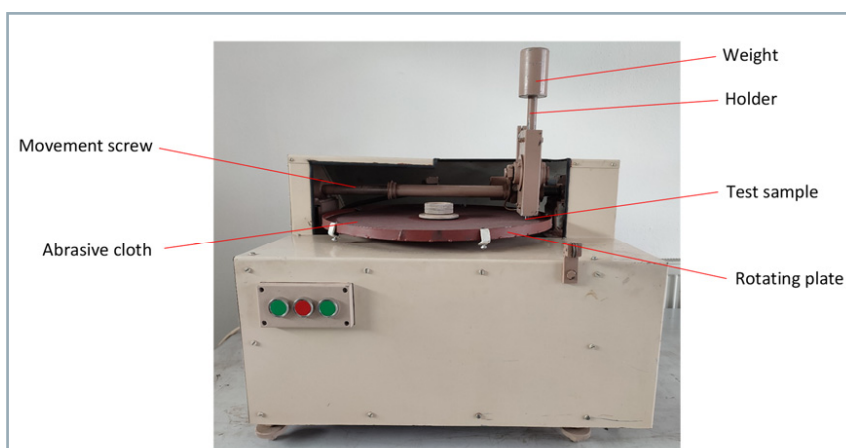


Fig. 2 Device for testing the resistance of materials to abrasive wear on an abrasive cloth

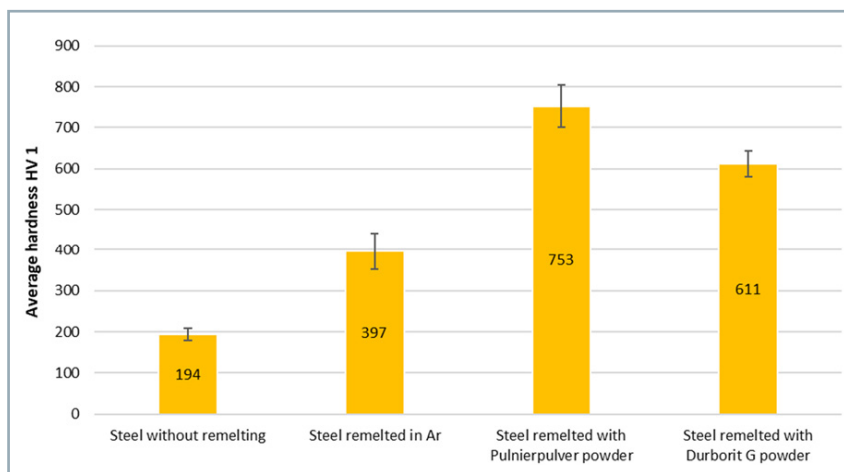


Fig. 3 Average values of hardness HV 1 in remelted layers measured horizontally

the sample surfaces with the applied Pulnierpulver powder contributed to a more significant increase in hardness compared to the samples with the

applied Durborit G powder. The enrichment of remelted layers with nitrogen is therefore more significant than enrichment with boron. The

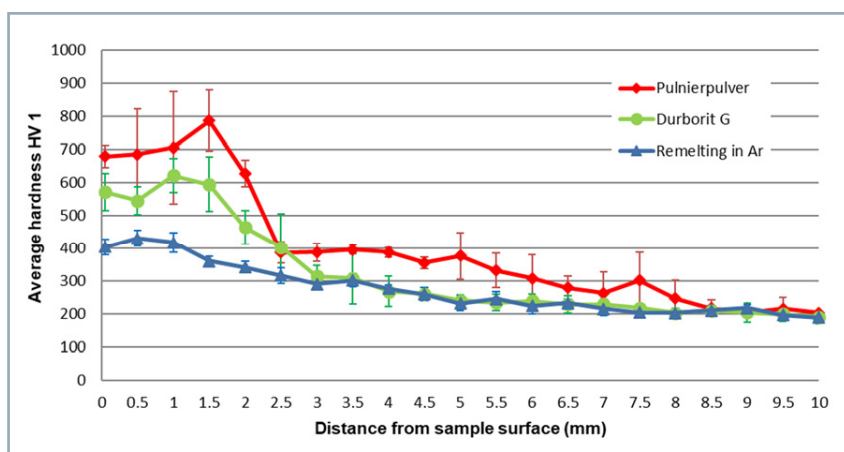


Fig. 4 The course of hardness HV 1 in remelted samples depending on the distance from the sample surface

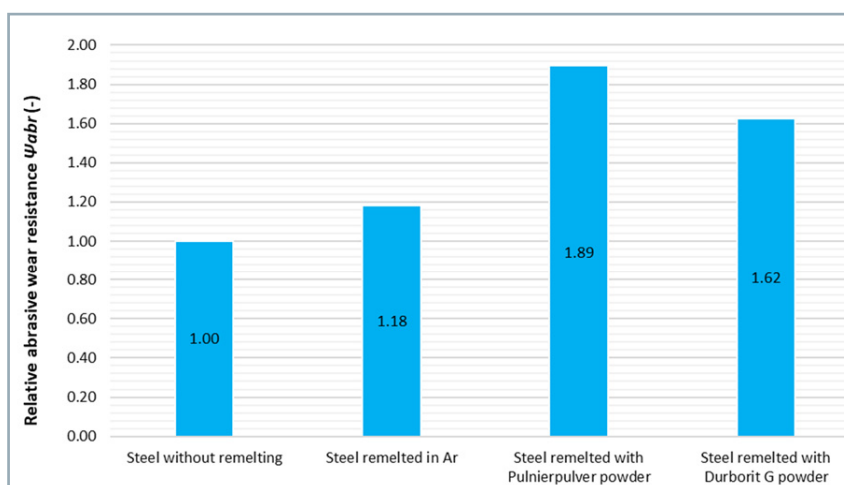


Fig. 5 Average weight losses of the examined samples during the abrasive wear resistance test

difference is about 140 HV 1 on average.

In both cases, a gradual increase in hardness values from the surface to the inside of the material is noticeable. In samples saturated with nitrogen (Pulnierpulver powder), hardness reached the maximum value of 787 HV 1 at a depth of 1.5 mm. For samples saturated with boron (Durborit G powder), the maximum hardness value of 622 HV 1 was recorded at a depth of 1 mm. The depth of remelting was approximately the same in both cases and reached the level of 2.5 mm. The reached values of hardness and thickness of the layers with a significant increase in hardness after remelting are comparable to the results achieved by Dziedzic and Adamiak (2010).

From the graphic representation of the vertical course of hardness (Fig. 4), relatively wide areas of thermal influence can be identified in both cases. These areas are characterized by slightly increased hardness values compared to the base material without thermal influence. The interface between the remelted layer and the heat-affected area is relatively sharp, especially for samples with remelted Pulnierpulver powder. In this case, hardness decreased between a 1.5 and 2.5 mm depth by 384 HV 1, i.e., by almost half. For samples with Durborit G powder remelting, the hardness drop is similar and represents 49.7% of the highest value reached in the remelted layer.

The hardness curves in the vertical direction show that there is a relatively wide zone of thermal influence, extending to a depth of approximately 8 mm for samples remelted in the presence of Pulnierpulver powder and to a depth of approximately 5 mm for samples remelted in the presence of Durborit G powder. For comparison, Fig. 4 also shows a curve of the hardness values HV 1 of samples remelted in the Ar shielding gas atmosphere without the presence of powders. The indicated widths of heat-affected areas are also visible on the images of macrostructure (Fig. 6a and Fig. 7a).

Resistance to abrasive wear

All examined variants were tested for resistance to abrasive wear on an abrasive cloth. Resistance to abrasive wear was determined using the

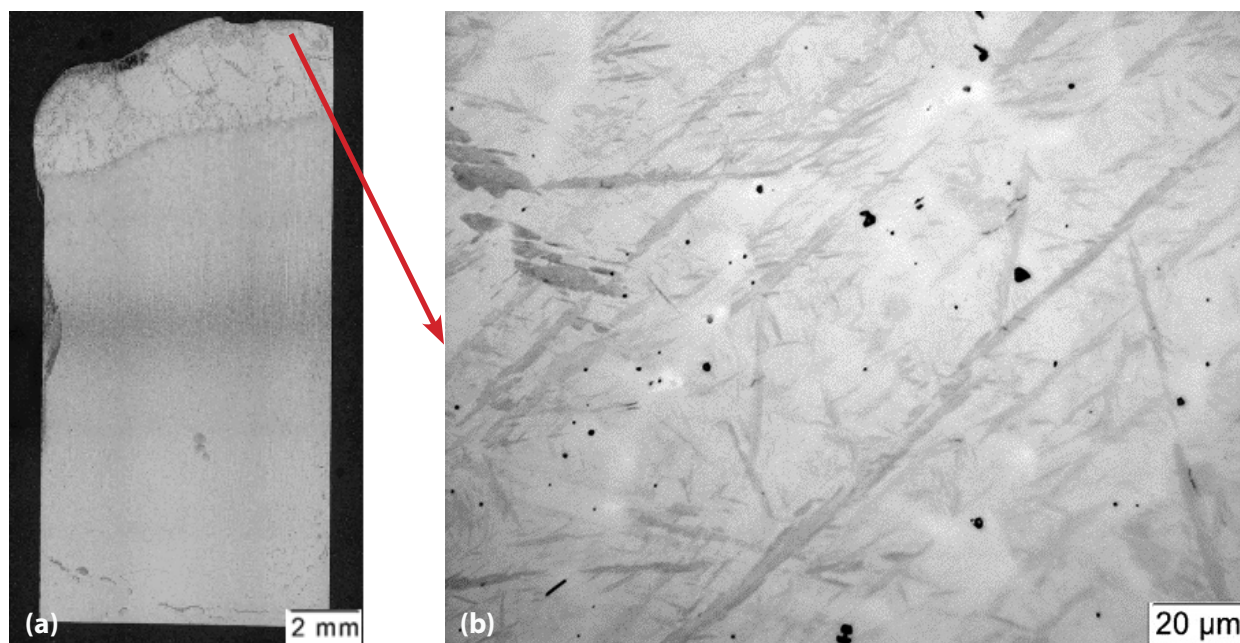


Fig. 6 Cross-section macrostructure of the sample with remelted Pulnierpulver powder (a) and the microstructure of remelted layer obtained by LOM (b)

average weight loss of samples reached by the defined process of abrasive wear according to Eq. (1). The graphic representation of relative resistance to abrasive wear of examined samples is shown in Fig. 5.

As expected, the lowest resistance to abrasive wear was achieved by the samples of the examined steel without remelting. This value was used as a basis for comparing the wear resistance achieved by individual TIG remelting methods.

The highest value of relative resistance to abrasive wear was found for samples remelted in the presence of Pulnierpulver powder (a value of 1.89). The relative resistance to abrasive wear of the samples remelted in the presence of Durborit G powder was 1.62, i.e., by 16.6% less

than for samples remelted in the presence of Pulnierpulver powder. Therefore, it can be concluded that the enrichment of remelted layers with nitrogen has a more significant effect on resistance to abrasive wear than enrichment with boron. This fact is also confirmed by the observation of microstructure of the remelted layers (Fig. 6 and Fig. 7).

Metallography

The TIG remelting of powders on the surface of the examined steel samples led to a significant change in microstructure in these remelted layers. The resulting phase composition and phase morphology were largely determined by the type of remelted powder. The macrostructures of the examined samples are shown in Figs 6a and 8a. The microstructures of

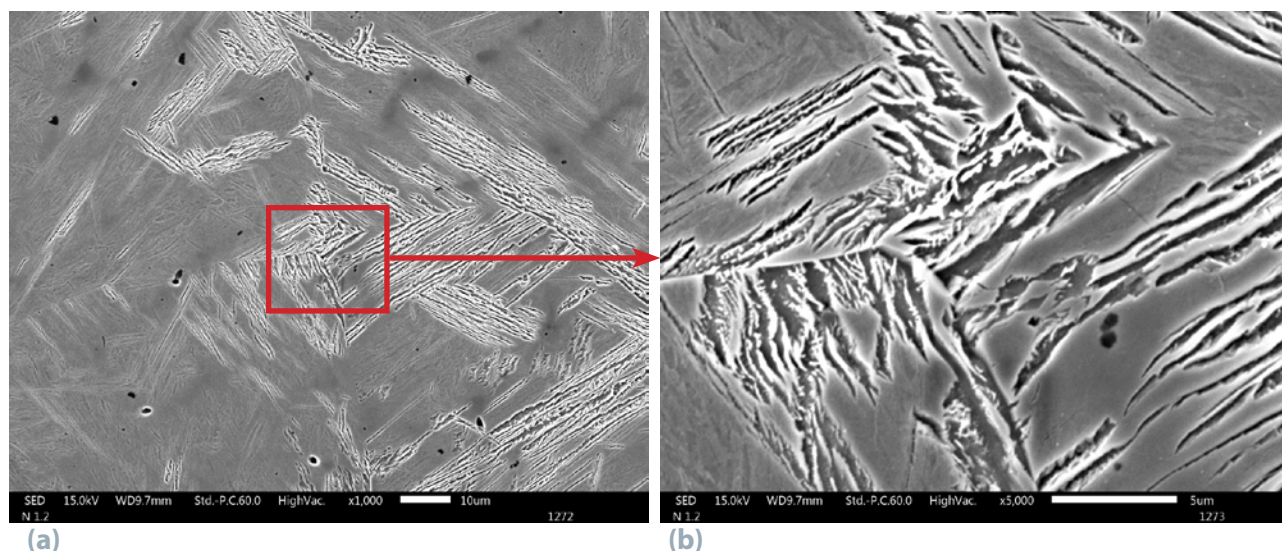


Fig. 7 Details of the microstructure of the Pulnierpulver powder remelted layer obtained by SEM at magnifications 1000× (a) and 5000× (b)

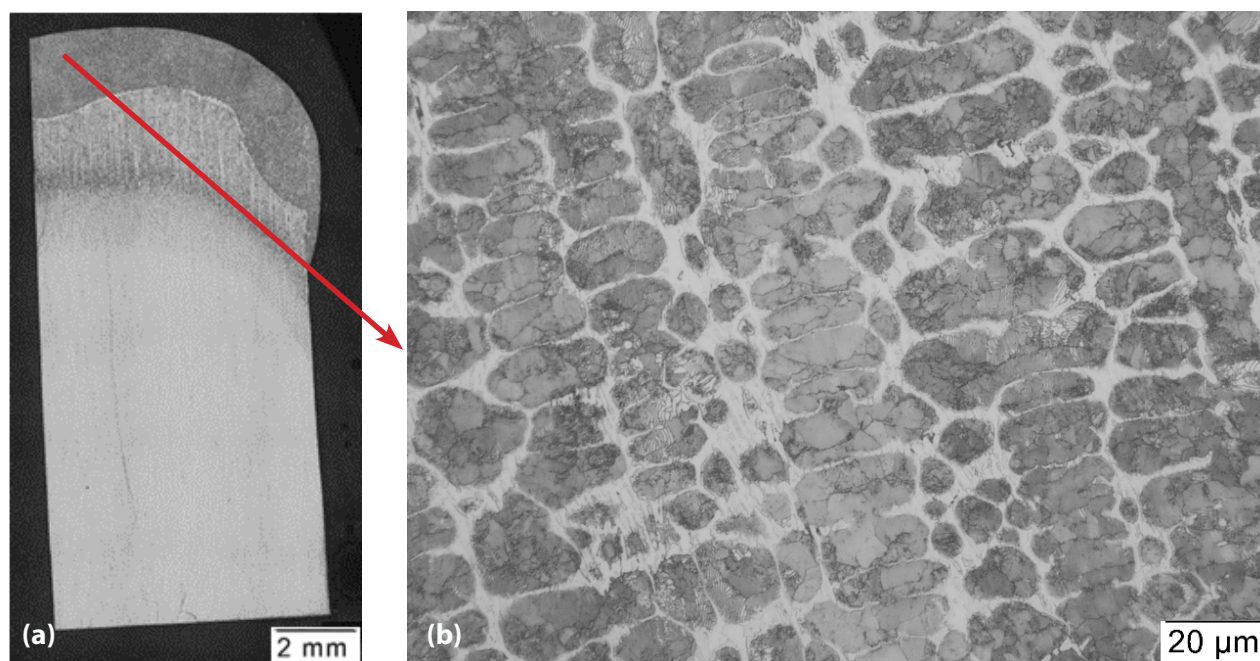


Fig. 8 Cross-section macrostructure of the sample with remelted Durborit G powder (a) and the microstructure of the remelted layer obtained by LOM (b)

the remelted layers at different magnifications are shown in Figs 6b and 7, respectively in Figs 8b and 9.

The remelting of the examined steel in the presence of Pulnierpulver powder produced a dendritic matrix consisting of fine martensite (enriched with nitrogen) and residual austenite, which is clearly visible on the SEM details of microstructure (Fig. 7).

In addition, coarse needle-like formations occur in microstructure. Such a microstructure contributes to the greatest extent to the increase in hardness and resistance to abrasive wear of the remelted layer in the presence of Pulnierpulver powder. Thus, the presence of nitrogen

significantly increased the hardenability in the remelted area and, in addition, caused the enrichment of martensite with nitrogen, which led to its increased hardness compared to the microstructure created by simple remelting without the presence of powder (Kováč et al., 2022).

By remelting the examined steel in the presence of Durborit G powder, a dendritic microstructure was created (Fig. 8), which was formed by fine lamellar pearlite inside dendrites and a network formed by iron carboborides in the interdendritic spaces (Kováč et al., 2014; Falat et al., 2019). This microstructure is visible in the SEM details of microstructure (Fig. 9).

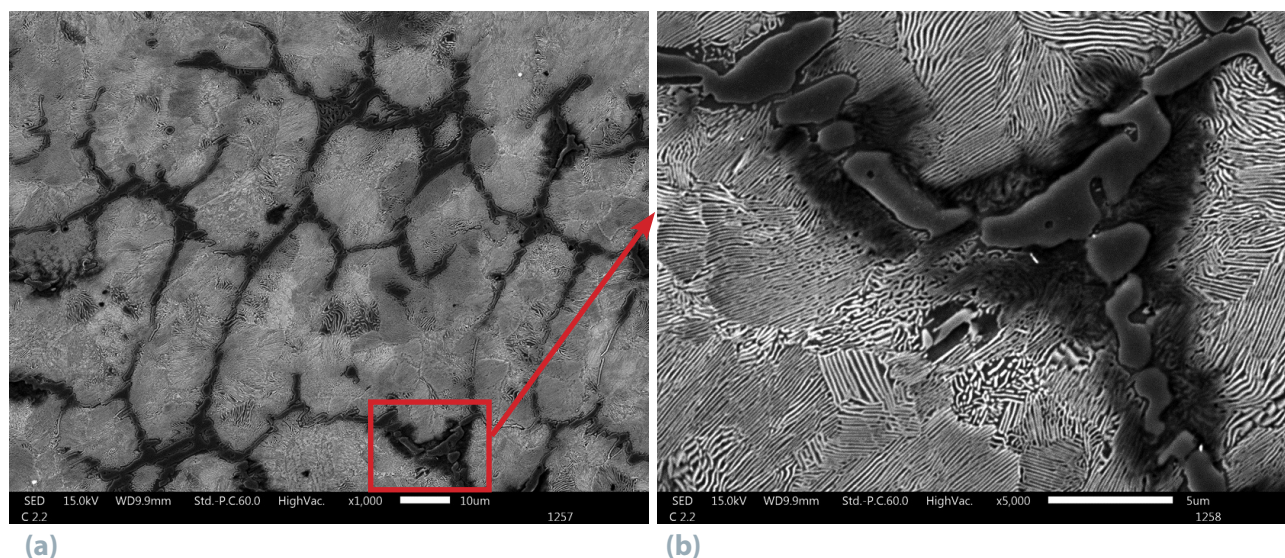


Fig. 9 Details of the microstructure of the Durborit G powder remelted layer obtained by SEM at magnifications 1000× (a) and 5000× (b)

Because the majority of microstructure consists of lamellar pearlite, the values of hardness and resistance to abrasive wear when remelting boron-containing powder did not reach such high values as when remelting nitrogen-containing powder.

Conclusion

In the presented research, the influence of steel 41CrAlMo7 remelting was examined through TIG remelting in the presence of two types of nitrogen-rich or boron-rich powders for its hardness and resistance to abrasive wear. The following findings result from the achieved results:

- Nitrogen-containing powder is more suitable for the given material during TIG remelting than boron-containing powder in terms of the obtained microstructure of the remelted layer and its resulting properties (hardness and resistance to abrasive wear).
- When the Pulnierpulver powder was remelted, an almost four times increase in hardness and an almost two times increase in wear resistance was achieved compared to steel without remelting. When Durborit G powder was remelted, a more than three times increase in hardness and a more than 1.5 times increase in resistance to abrasive wear compared to steel without remelting was achieved.
- In both cases of remelting in the presence of powder (Pulnierpulver with nitrogen content, or Durborit G with boron content), there was a significant increase in hardness and resistance to abrasive wear compared to simple remelting in a shielding gas atmosphere of argon without the presence of powder, or state without remelting. Thus, the significant influence of the elements contained in the remelted powders on the change of the microstructure of remelted layers and their properties was confirmed.
- The TIG remelting of powders with a suitable chemical composition makes it possible to achieve a significant and stable increase in hardness and resistance to abrasive wear in remelted layers without need for further heat treatment, while the resulting layers reach a thickness of more than 1 mm during a very short time of exposure to elevated temperature.

The presented procedure of TIG surface remelting of powders containing a certain element represents a cheap, accessible, and fast way of creating surface layers with increased hardness and wear resistance. This gives the presented method future possibilities of its use for increasing the wear resistance of functional parts of machines for agriculture, earthmoving, etc.

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