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Effect of Plasma Nitriding on Mechanical Properties of Tensile Specimen of 25Cr2Ni4W Low Alloy Steel

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This study investigates the effect of plasma nitriding on the tensile specimens of 25Cr2Ni4W low-alloy steel, aiming to enhance their mechanical and tribological surface properties. The experimental analysis compares treated and untreated specimens to evaluate the influence of nitrogen diffusion on the material performance. Results reveals that plasma nitriding led to an increase in elastic resistance (R_e) and a decrease in plastic resistance (R_p), attributed to self-induced heating during treatment. Optical microscopy (OM) confirmed the formation of a distinct nitride layer on the treated surface. The enhancement of the elastic phase contributes to an increase in elongation (L_1), indicating improved ductility. Furthermore, nanoindentation tests demonstrate a significant rise in nanohardness for the nitrided samples compared to the untreated ones, confirming the strengthening effect of nitrogen incorporation and nitride phase formation.

Key words: plasma nitriding, tensile specimen, plastic resistance, elastic resistance, nanohardness, low-alloy steel.

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У цьому дослідженні вивчається вплив плазмового азотування на зразки низьколеґованої криці 25Cr2Ni4W, що піддаються розтягуванню, з метою поліпшення їхніх механічних і трибологічних властивостей поверхні. В експериментальній аналізі порівнюються оброблені та необроблені зразки для оцінки впливу дифузії Нітроґену на характеристики матеріялу. Результати показують, що плазмове азотування привело до збільшення пружнього опору (R_e) і зменшення пластичного опору (R_p), що пояснюється самоіндукованим нагріванням під час обробляння. Оптична мікроскопія підтвердила утворення чіткого нітридного шару на обробленій поверхні. Приріст пружньої фази сприяє збільшенню подовження (L_1), що свідчить про поліпшення пластичности. Крім того, випробування на наноіндентацію демонструє значне підвищення нанотвердости для азотованих зразків у порівнянні з необробленими, що підтверджує зміцнювальний ефект включення Нітроґену й утворення нітридної фази.

Ключові слова: плазмове азотування, зразок на розтяг, пластичний опір, пружній опір, нанотвердість, низьколеґована криця.

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1. INTRODUCTION

Surface modification of metallic materials is essential for improving their service performance in mechanical, tribological, and corrosive environments. Among various surface engineering techniques, plasma nitriding has gained significant attention due to its ability to enhance surface hardness, wear resistance, fatigue strength, and corrosion resistance without compromising the bulk properties of the substrate [1–3]. The process involves the diffusion of nitrogen atoms into the surface of a metallic material under low-pressure plasma at elevated temperatures, typically between 450°C and 600°C, forming a nitrogen-enriched layer composed of hard nitride phases [4, 5].

Unlike conventional gas or salt bath nitriding, plasma nitriding offers several advantages such as faster diffusion kinetics, shorter treatment durations, minimal distortion, and the ability to treat components with complex geometries [6–8]. The plasma environment allows precise control of critical process parameters, including temperature, pressure, gas composition, and bias voltage, enabling the tailoring of the surface microstructure and properties to specific industrial needs [9–11]. These advantages have made plasma nitriding a preferred surface treatment in the automotive, aerospace, tooling, and energy sectors, where components are frequently subjected to severe mechanical and thermal loading [12–14].

During plasma nitriding, nitrogen diffuses into the metallic substrate, forming a compound layer (often called the ‘white layer’) composed mainly of ε-$Fe_{2-3}N$ and γ'-$Fe_{2-3}N$ phases, followed by a diffusion zone rich in dissolved nitrogen [15, 16]. The compound layer contributes significantly to surface hardness and wear resistance, while the diffusion zone improves fatigue performance through the generation of beneficial compressive residual stresses [17, 18]. These residual stresses act to inhibit crack initiation and propagation, thereby enhancing the fatigue life of nitrided components [6, 19]. Furthermore, the formation of stable nitride compounds and the reduction in surface porosity can improve the corrosion resistance of steels and alloys treated by plasma nitriding [2, 4]. This effect is particularly relevant for applications in aggressive environments, such as marine, chemical processing, and aerospace industries [5, 9]. The relatively low temperatures used in plasma nitriding ensure that dimensional stability is preserved, making it suitable for precision-engineered components where tight tolerances must be maintained [7, 8]. Recent research has focused on optimizing plasma nitriding parameters to achieve desired surface characteristics and to understand the relationship between process variables and resulting properties. Studies reported in 'Metallofizika i Noveishie Tekhnologii' have contributed valuable insights into the mechanisms of nitrogen diffusion, phase formation, and structural transformations under glow-discharge conditions [7, 12, 14]. For example, glow-discharge nitriding and multiplex plasma treatments have been used to improve both hardness and oxidation resistance in ferrous and titanium-based alloys. Similarly, recent investigations on low-temperature plasma nitriding of steels have demonstrated the formation of expanded austenite (S-phase) with superior wear and corrosion performance, broadening the applicability of the technique to stainless steels and other low-alloy systems [8]. In this context, the present work aims to investigate the influence of plasma nitriding parameters specifically temperature, gas composition, and bias voltage on the microstructure and mechanical properties of low-alloy steel. The study is designed to elucidate the relationship between process conditions, the morphology of the nitrided layers, and the resulting mechanical performance. The findings contribute to the broader understanding of plasma-assisted thermochemical treatments, in alignment with recent developments reported in 'Metallofizika i Noveishie Tekhnologii' and other materials science journals [12, 14].

2. EXPERIMENTAL PROCEDURE

The low-alloy steel 25Cr2Ni4W finds extensive application in the manufacturing of pipes, railroad tracks, automobile and aircraft bodies, as well as in onshore and offshore structural engineering. The chemical composition of this low alloying steel is detailed in Table 1. The presence of nickel and chromium imparts excellent tensile strength, wear resistance, and ductility to 25Cr2Ni4W, while manga-

TABLE 1. Chemical composition of 25Cr2Ni4W.

25 Cr2Ni4W	C%	Mn	Cr	Ni	W	P	S
wt.%	0.28	0.5	1.5	3.97	0.73	0.02	0.012

nese enhances its hardenability. In addition, tungsten contributes to improved thermal stability and secondary hardening, making this alloy suitable for components operating under high stress or temperature conditions. The investigation of surface treatments such as plasma nitriding provides valuable insight into the diffusion mechanisms and resulting microstructural transformations within this alloy.

2.1. Condition of treatment

Figure 1 shows the standardized tensile specimen prepared from the 25Cr2Ni4W low-alloy steel. The specimen was machined according to the standard to ensure the accuracy and repeatability of the tensile tests. Its geometry, with a reduced central section, allows uniform distribution of stress during loading and accurate measurement of elongation. The schematic diagram of the specimen is also presented to il-

Fig. 1. Tensile test specimen.

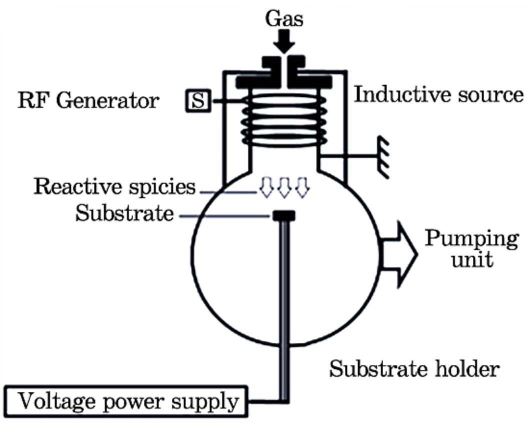

Fig. 2. Plasma nitriding system setup [13].

TABLE 2. Parameters of experience.

Parameter	Value
First pressure	$3\cdot10^{-5}$ mbar
W	400 W
V	3.5 kV
Holding time	60 min

lustrate its dimensions and configuration.

The standard experimental configuration of the PIII system is graphically illustrated in Fig. 2, which includes a spherical vacuum chamber of 930 mm diameter. The vacuum chamber was pressurized to $8\cdot10^{-6}$ mbar, then filled with nitrogen gas to $8\cdot10^{-2}$ mbar. Treatment time was 60 minutes. Alim and colleagues [13] optimized the PIII treatment parameters (frequency, negative bias voltage) mentioned in Table 2 using the same PIII system.

The nitriding conditions were carefully selected to ensure optimal nitrogen diffusion in the low-alloy steel. An initial pressure of $3\cdot10^{-5}$ mbar ensures adequate vacuum to purify the chamber before gas introduction. The applied power of 400 W and voltage of 3.5 kV promote the formation of stable and energetic plasma. Finally, a holding time of 60 minutes allows for uniform nitrogen penetration into the material's surface in Table 2.

3. RESULTS AND DISCUSSION

Table 3 summarizes the mechanical properties of the low-alloy steel 25Cr2Ni4W before and after plasma nitriding. The initial diameter ($D_0 = 10$ mm) was identical for both specimens, ensuring comparable testing conditions. After the tensile test, the final diameters were $D_1 = 6$ mm for the untreated and $D_1 = 8$ mm for the nitrided specimen, confirming that the treated steel exhibited less plastic deformation due to surface hardening. The maximum load and ultimate tensile strength increased from $61\cdot10^3$ N (1214 MPa) to $62\cdot10^3$ N (1636 MPa), indicating a significant improvement in mechanical strength after nitriding. Similarly, the yield strength rose from 995 MPa to 1402 MPa, demonstrating enhanced resistance to elastic deformation. However, the elongation at fracture decreased from 20.4% to 16.6%, reflecting the expected reduction in ductility following surface hardening.

The area of tensile specimen

$$S = \pi D^2/4. \tag{1}$$

TABLE 3. Results of treatment.

Designation	25Cr2Ni4W	
Settings	Untreated	Treated
D_0 [mm]	10	10
D_1 [mm]	6	8
F_p [N]	$61\cdot10^3$	$62\cdot10^3$
R_p [MPa]	1214	1636
F_e [N]	$50\cdot10^3$	$54\cdot10^3$
R_e [MPa]	995	1402
L_0 [mm]	50	50
L_1 [mm]	60.2	58.3
A [%]	20.4	16.6

The plastic resistance

$$R_p = F_p/S. \tag{2}$$

Elastic resistance

$$R_e = F_e/S. \tag{3}$$

Elongation on %

$$A\% = (L_1 - L_0)/L_0. \tag{4}$$

3.1. Microstructure

Figure 3, *a* and Figure 3, *b* show the microstructure of the 25Cr2Ni4W low alloy steel untreated tensile sample and after plasma nitriding treatment. As seen in Fig. 3, *a*, the untreated tensile sample consists of ferrite and pearlite phases. In Figure 3, *b*, the microstructure shows three different regions inwards from the surface. These regions consist of the diffusion layer. In our research, we have also tested the change in strength of bonded joints with different heat treatment methods on specimens that have been surface treated in different ways.

3.2. Effect of Plasma Nitriding on Strength

As shown in Fig. 4, the results illustrate the effect of the plasma nitriding treatment on the tensile behaviour of the material. The materi-

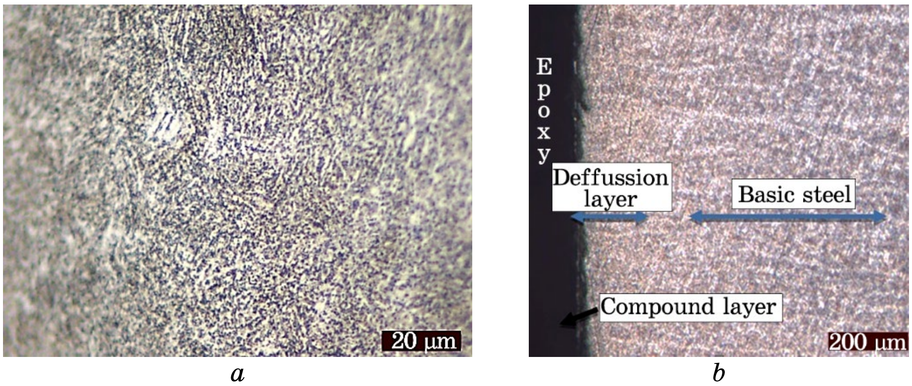

Fig. 3. Microstructure of the 25Cr2Ni4W low alloy steel treated (*b*) and untreated (*a*) tensile sample.

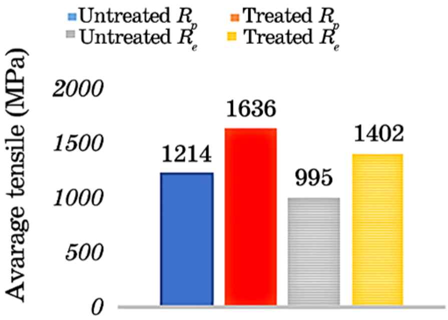

Fig. 4. Effect of nitriding treatment on the plastic resistance (R_p) and elastic resistance (R_e).

al's resistance to permanent deformation increased, as evidenced by the rise in ultimate tensile strength (R_p) from 1214 MPa in the untreated specimen to 1636 MPa after treatment. Similarly, the yield strength (R_e) improved from 995 MPa to 1402 MPa, indicating an enhanced ability of the material to withstand elastic deformation before yielding. The simultaneous increase in both R_p and R_e clearly demonstrates the effectiveness of the plasma nitriding process in strengthening the overall mechanical properties of the steel.

Figure 5 illustrates the comparison of elongation (in mm) between the tensile specimens before and after plasma nitriding. The untreated specimen exhibited a higher elongation of 60.2 mm, whereas the nitrided specimen showed a reduced elongation of 58.3 mm. This decrease in elongation indicates a loss of ductility resulting from the plasma nitriding process. Plasma nitriding, a surface hardening technique based on nitrogen diffusion into the metal surface, enhances

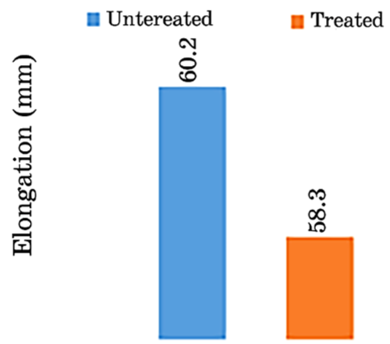

Fig. 5. Elongation of the tensile specimen.

hardness, wear resistance, and fatigue strength. However, it also restricts dislocation motion and introduces residual stresses, which can limit plastic deformation and consequently reduce elongation. Therefore, the results demonstrate that plasma nitriding under the applied conditions (3.5 kV, 60 minutes, 400 W) led to a slight reduction in elongation, reflecting the typical trade-off between increased surface hardness and decreased ductility.

3.3. Hardness Measurement

The nanohardness analysis (see Fig. 6) provides valuable insights into the effect of plasma nitriding on the mechanical behaviour of the 25Cr2Ni4W steel. The untreated specimen serves as the baseline, exhibiting the natural hardness of the core material. In contrast, the

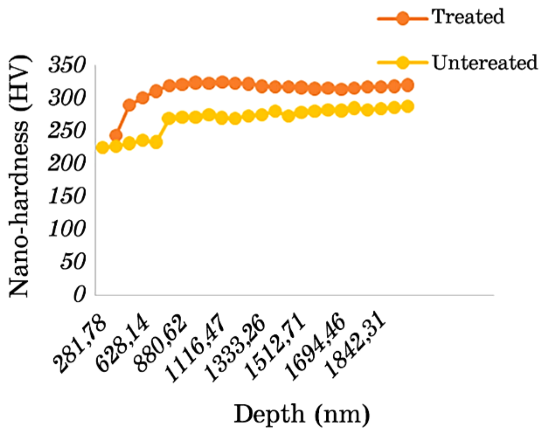

Fig. 6. Hardness measurement.

treated specimen shows significantly higher nanohardness values, confirming the formation of hard nitride phases on the surface. The hardness depth profile reveals a sharp increase near the surface corresponding to the nitride zone followed by a gradual decrease toward the core. This gradient reflects the diffusion of nitrogen atoms, which form hard nitride compounds in the outer layer. The markedly higher surface hardness of the treated specimen indicates a substantial improvement in wear resistance. Moreover, the increased hardness and the depth of the hardened layer demonstrate the effectiveness of the plasma nitriding process in enhancing surface durability and resistance to fatigue. The mechanical behaviour curves further confirm improved elastic properties, as evidenced by the increase in yield strength (R_e), allowing the material to sustain higher loads without permanent deformation. Despite the hardening effect, the material retains acceptable ductility, as shown by its elongation (L_1), ensuring a good balance between hardness and toughness. Overall, the results highlight the formation of a hard, wear-resistant nitride layer that significantly improves the material tribological performance, making it well suited for high-wear mechanical applications such as gears, cams, and other machine components.

4. CONCLUSION

As determined, the plasma nitriding treatment applied to 25Cr2Ni4W low-alloy steel significantly improves its mechanical and tribological surface performance. The systematic investigation has revealed a clear correlation between nitrogen diffusion and the resulting modification of surface properties. The analysis showed that the elastic tensile strength (R_e) increases notably after nitriding, indicating a strengthening of the elastic phase and an enhancement in the material ability to withstand higher loads without permanent deformation. Conversely, a slight decrease in plastic tensile strength (R_p) was observed, mainly attributed to the self-heating effect within the vacuum chamber during treatment.

Optical microscopy confirmed the formation of a continuous and compact nitride layer at the surface, while nanoindentation measurements evidenced a pronounced increase in nanohardness, validating the presence of hard nitride phases. The improvement in elongation (L_1) further indicates that the material retains acceptable ductility despite the surface hardening effect, ensuring a good balance between strength and toughness.

Proceeding from the performed research, it can be concluded that plasma nitriding is an efficient surface engineering process for enhancing the wear resistance, hardness, and durability of 25Cr2Ni4W steel without significantly compromising its ductility. The results highlight the potential application of this treatment for high-wear mechanical components such as gears, cams, and precision-engineered parts operating under severe loading conditions.

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AUTHORS' CONTRIBUTIONS

Ouafa Hamidane performed all the experimental work, prepared the figures, and wrote the original draft of the manuscript. Brahim Chermime proposed the research topic, supervised the study, and contributed to the correction and partial writing of the manuscript. Mohamed Mounes Alim carried out the experimental work in his laboratory, and all experimental results were obtained under his supervision. Mamoun Fellah interpretation of the results. All authors read and approved the final version of the manuscript.

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