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Surface Modification of Steel 1.2343 (EN ISO 4957) by Ion Nitriding

Desislava Dimova
Technical University of Sofia,
Branch Plovdiv
Plovdiv Bulgaria
Center of competence "Smart mechatronic, eco-and energy-saving systems and technologies"
Plovdiv, Bulgaria
d.dimova@tu-plovdiv.bg

Boyan Dochev
Technical University of Sofia,
Branch Plovdiv
Plovdiv Bulgaria
Center of competence "Smart mechatronic, eco-and energy-saving systems and technologies"
Plovdiv, Bulgaria
dochev@tu-plovdiv.bg

Teodor Solakov
Technical University of Sofia,
Branch Plovdiv
Plovdiv Bulgaria
teodorsolakov@std.tu-plovdiv.bg

Mikaela Dubaradzieva
Technical University of Sofia,
Branch Plovdiv
Plovdiv Bulgaria
mdubaradzieva17@gmail.com

Nikolay Ivanov
Technical University of Sofia,
Branch Plovdiv
Plovdiv Bulgaria
nai_78@abv.bg

Abstract*— The present study investigates the surface modification of tool steel 1.2343 (EN ISO 4957) by ion nitriding. Prior to the chemical–thermal treatment, the specimens were subjected to heat treatment consisting of vacuum quenching followed by triple tempering, ensuring structural stabilization before the diffusion process. Ion nitriding was carried out under two temperature–time regimes, namely 490°C for 16 h and 500°C for 11 h, in order to evaluate their influence on microstructure, hardness distribution, and tribological behaviour. Microstructural analysis revealed the absence of a compound (white) layer composed of ε and γ' phases, while a diffusion layer with a relatively uniform thickness of up to ~250 µm was observed. The effect of the nitriding parameters on surface hardness and hardness depth profiles—from the surface to the core—was systematically analyzed. In addition, tribological tests were performed to determine the coefficient of friction and wear characteristics of the treated surfaces. The results indicate that the applied nitriding regimes significantly influence the development of the diffusion layer and the surface properties, with the regime at 500°C providing a more favorable balance between hardness and tribological performance.

***Keywords*— coefficient of friction; ion nitriding; microstructure; vacuum quenching and tempering**

I. INTRODUCTION

Hot-work tool steels are widely used under conditions of elevated temperatures and significant mechanical loads, typical for processes such as die casting, hot forging, and extrusion. Among them, steel 1.2343 (EN ISO 4957), belonging to the Cr–Mo–V class of tool steels, is characterized by a favorable combination of high strength, toughness, thermal fatigue resistance, and stability at elevated temperatures. These properties make it widely applied in the manufacturing of tools operating under severe service conditions [1–3].

The service performance of this steel largely depends on the applied heat treatment. Vacuum quenching combined with multiple tempering represents an established technological approach for obtaining a stable tempered structure with finely dispersed alloy carbides [4–6]. Stepwise heating to the austenitic region ensures a more uniform temperature distribution throughout the component, reduces thermal stresses, and promotes partial dissolution of carbides [7]. Gas cooling in vacuum furnaces, most commonly using nitrogen, allows minimization of distortion and achievement of high dimensional accuracy [8].

After quenching and tempering in the temperature range of 500–600 °C, a secondary hardening effect is observed, associated with the precipitation of fine alloy

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carbides. This process leads to increased resistance to hardness reduction and structural stability during operation at elevated temperatures [9–11]. The influence of alloying elements is essential for the formation of these properties. Chromium increases hardenability and participates in the formation of carbides and nitrides, molybdenum improves heat resistance and reduces tempering brittleness, while vanadium forms stable fine carbides and nitrides that limit grain growth and structural changes at elevated temperatures, thereby enhancing wear resistance and microstructural stability [12–14]. Silicon also plays a significant role in tempering resistance and diffusion processes, as it delays martensite decomposition and contributes to maintaining higher hardness during service.

Despite the favorable bulk properties, the surface of hot-work tool steels remains susceptible to wear, adhesion, and thermal fatigue. To improve surface performance, thermochemical treatments such as ion (plasma) nitriding are widely applied [15–17]. The process is carried out at relatively low temperatures (450–550 °C) under glow discharge conditions, where ionized nitrogen interacts with and diffuses into the surface, forming a hardened layer [18]. Compared to conventional gas nitriding, plasma nitriding offers better control of process parameters, higher efficiency, and reduced environmental impact [19].

As a result of ion nitriding, a multilayer surface structure is typically formed, consisting of a compound (white) layer and a diffusion zone. The compound layer mainly contains iron nitrides, while the diffusion zone is characterized by the formation of fine alloy nitrides of elements such as Cr, Mo, and V, which significantly contribute to increased hardness and wear resistance [20–22]. The thickness of the diffusion layer and the hardness distribution in depth strongly depend on the process parameters, particularly nitriding temperature and time [23].

An increase in nitriding temperature leads to accelerated diffusion processes and higher surface hardness but may result in a steeper hardness gradient and a reduced effective depth of the hardened layer. Conversely, lower temperatures favor the formation of a more uniform diffusion zone with a smoother hardness profile [24,25]. Therefore, the selection of optimal ion nitriding parameters requires a balance between surface hardness and diffusion layer depth.

In this context, the present study is focused on analyzing the influence of different ion nitriding regimes on the microhardness distribution and diffusion layer characteristics of steel 1.2343 (EN ISO 4957), previously subjected to vacuum quenching and multiple tempering. The main objective is to establish the relationship between process parameters and the formation of the nitrided layer, as well as to determine an optimal regime providing the best combination of high surface hardness and sufficient diffusion layer depth.

The scientific novelty of the present study consists in establishing the relationship between ion nitriding parameters, diffusion layer development, hardness distribution, and tribological behavior of vacuum-quenched and tempered 1.2343 hot-work tool steel under different plasma nitriding regimes.

II. MATERIALS AND METHODS

The present study focuses on tool steel 1.2343 (EN ISO 4957), specified according to the standard BDS EN ISO 4957:2018 [26], with its chemical composition given in Table 1. This steel is primarily used for manufacturing tooling for hot plastic deformation processes. Its chemical composition complies with the standard requirements for Cr–Mo–V hot-work tool steels.

TABLE 1 CHEMICAL COMPOSITION OF STEEL 1.2343

[WT %]

Element	C	Si	Mn	Cr	Mo	V	Fe
wt.%	0.36 – 0.42	0.80 – 1.20	0.30 – 0.50	4.80 – 5.50	1.20 – 1.50	0.85 – 1.15	Rest

Cylindrical specimens with a diameter of φ30 mm and a thickness of 3 mm were machined from the as-received material. The specimens were prepared for microstructural analysis and microhardness measurements. Prior to heat treatment, the specimen surfaces were mechanically finished and cleaned in order to remove contaminants and ensure good repeatability of the results.

Tool steel 1.2343 (EN ISO 4957), belonging to the Cr–Mo–V class of hot-work tool steels, is characterized by a favorable combination of high strength, toughness, thermal fatigue resistance, and stability at elevated temperatures. Its performance strongly depends on the applied heat treatment, which provides the required balance between hardness and toughness, as well as an appropriate microstructure for subsequent surface modification.

The specimens were subjected to heat treatment consisting of vacuum quenching followed by triple tempering. Heating prior to quenching was carried out in a stepwise manner up to the austenitic region in order to ensure uniform temperature distribution throughout the material, reduce thermal stresses, and promote the dissolution of alloy carbides. The following temperature–time stages were applied: 650°C with a holding time of 30 min, 850°C for 20 min, and 1040°C for 20 min. The heating was performed under vacuum conditions, which prevented oxidation and decarburization and ensured a high surface quality.

After reaching the austenitic temperature and homogenization of the austenite, cooling was carried out in a nitrogen atmosphere at a pressure of 2.3 bar. This ensured a sufficiently high cooling rate for the formation of a martensitic structure with minimal distortion. As a result of quenching, a structure consisting of martensite and retained austenite was obtained, which required subsequent tempering for stabilization. After quenching, the specimens were subjected to triple tempering at temperatures of 500 °C, 520 °C, and 540 °C. During tempering, precipitation of fine alloy carbides occurs, leading to increased resistance to hardness reduction and improved stability of properties

at elevated temperatures. The applied heat treatment resulted in the formation of a stable tempered martensitic structure with a uniform distribution of carbides, providing a suitable substrate for subsequent ion nitriding.

Ion (plasma) nitriding was carried out in a specialized installation under two different temperature–time regimes: 490°C for 16 h and 500°C for 11 h. The process was performed in a gaseous atmosphere consisting of nitrogen and hydrogen under glow discharge conditions. The working gas pressure (ammonia) was maintained in the range of 0.8–0.9 bar. These conditions ensured effective surface activation and enhanced diffusion processes. After nitriding, the specimens were cooled in a controlled environment within the working chamber in order to minimize oxidation and preserve the formed surface layer. The selected regimes allowed investigation of the influence of temperature–time parameters on the formation of the diffusion layer and the hardness distribution in depth.

The thickness of the individual zones of the nitrided layer was determined by optical microscopy using an inverted optical microscope (Kern OLM 171, Kern GmbH, Germany), equipped with a color digital camera (ODC 832) and image analysis software. Prior to metallographic examination, the specimens were prepared by standard procedures including wet grinding and polishing with diamond paste and lubricant, followed by chemical etching using a 4% alcoholic HCl solution for 14 s.

Microhardness measurements were performed using a HVS-1000 hardness tester (Jinan Hengxu Test Technology Co., Ltd., Jinan, China) after heat and thermochemical treatment, including measurements along the depth of the nitrided layer. The tests were carried out using the Vickers method with a load of 0.1 kg ($HV_{0.1}$), in accordance with BDS EN ISO 6507-1:2024 [27].

Tribological tests were conducted to determine the coefficient of friction and to evaluate the influence of ion nitriding on the tribological behavior of 1.2343 steel. The experiments were performed under dry sliding conditions at room temperature. A normal load of 10 N was applied, the sliding speed was 100 rpm, and the test duration was 3 min (sliding distance of 24 m). A ball-on-disc configuration was used with three balls of 6.37 mm diameter, positioned at 120° relative to each other. The balls were located on a diameter of 25 mm relative to the rotational axis and were made of 100Cr6 steel with a hardness of 830 $HV_{0.1}$.

III. RESULTS AND DISCUSSION

The optical metallographic analysis of specimens subjected to ion nitriding at 490°C/16 h and 500°C/11 h reveals the formation of a clearly defined diffusion layer without the presence of a compound (white) layer (Figures 1 and 2). In both regimes, a gradual transition between the nitrided layer and the substrate is observed, indicating a uniform progression of diffusion processes.

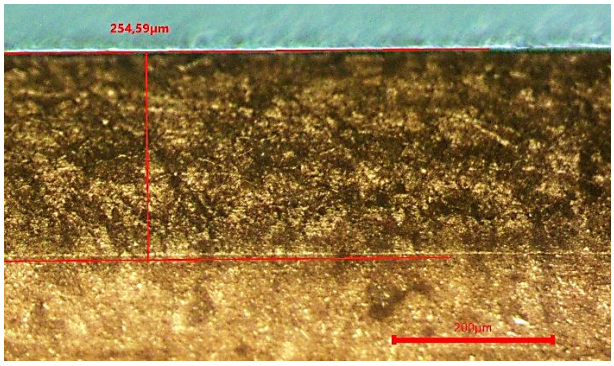

Fig. 1. Microstructure of the nitrided layer of steel 1.2343 after ion nitriding at 490°C for 16h

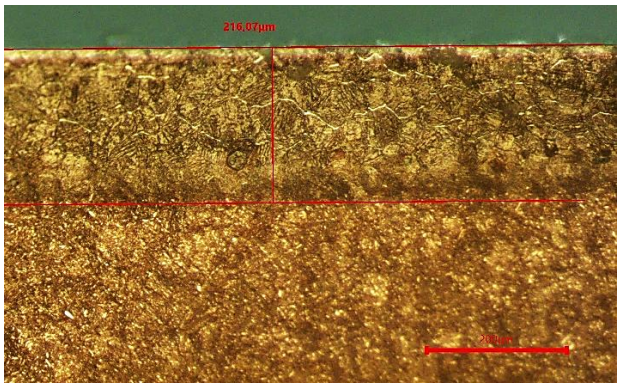

Fig. 2. Microstructure of the nitrided layer of steel 1.2343 after ion nitriding at 500°C for 11h

For the regime 490°C/16 h, a diffusion layer with a thickness of approximately 250µm is formed, characterized by a relatively uniform microstructure and a gradual transition toward the substrate. The microhardness profile shows high values near the surface (~627 $HV_{0.1}$), which remain relatively constant up to a depth of about 120 µm. With increasing depth, a gradual decrease in hardness is observed, reaching approximately 535 $HV_{0.1}$ at a depth of 300µm. This smooth decrease in hardness is consistent with the uniform nature of the diffusion layer. In contrast, for the regime 500°C/11 h, a thinner diffusion layer (~216 µm) is formed, characterized by a more pronounced transition to the substrate. However, the surface hardness is significantly higher, reaching values of approximately 698 $HV_{0.1}$. With increasing depth, a more pronounced decrease in hardness is observed, reaching about 553 $HV_{0.1}$ at the diffusion layer boundary and approximately 528 $HV_{0.1}$ at a depth of 300µm. The observed steeper hardness profile is consistent with the reduced layer thickness and more intensive surface hardening. A comparison of the microstructural features and hardness profiles indicates that at lower temperature and longer nitriding time (490°C/16h), a deeper and more uniform diffusion layer is formed, with a gradual variation of properties in depth. In contrast, at higher temperature and shorter time (500°C/11h), higher surface hardness is achieved at the

expense of reduced layer thickness and a steeper property gradient.

Ion nitriding is a diffusion-controlled process in which nitrogen penetrates the surface layer under glow discharge conditions, with temperature, time, and chemical composition playing a key role [7,12]. For steel 1.2343, containing alloying elements such as Cr, Mo, and V, the nitriding process leads to the formation of a complex microstructure consisting of nitrogen in solid solution in ferrite and dispersed nitride phases [10,15]. Under the investigated conditions, no compound (white) layer consisting of ε-$Fe_{2–3}N$ and γ′ -Fe_4N phases is observed, indicating that the process proceeds predominantly in the diffusion regime [9,12]. In this case, nitrogen diffuses into the material and interacts with alloying elements, leading to the formation of stable alloy nitrides such as CrN, VN, and Mo_2N [10,18]. Chromium, as the primary alloying element, shows a strong tendency to form CrN nitrides, which contribute to increased hardness and wear resistance [10,15]. Vanadium forms highly stable and finely dispersed VN nitrides, which enhance strengthening through a dispersion mechanism and hinder dislocation motion [18]. Molybdenum forms nitrides of the Mo_2N type, improving heat resistance and microstructural stability at elevated temperatures [6,10].

The formation of these nitride phases leads to a significant increase in surface hardness and improved resistance to plastic deformation. Furthermore, the fine and uniform distribution of nitrides contributes to a more homogeneous stress distribution under loading and reduces the tendency for localized wear [15,18]. The absence of a compound (white) layer is beneficial for service performance, as this layer, despite its high hardness, is characterized by increased brittleness and a tendency for crack initiation and propagation [17,21]. Therefore, the obtained structure, consisting primarily of a diffusion layer with dispersed nitrides, provides better adhesion to the substrate and improved wear resistance [18,22]. The comparison between the two regimes shows that at lower temperature and longer duration (490°C/16h), diffusion processes penetrate deeper into the material, resulting in a thicker diffusion layer [15,16]. At higher temperature (500°C/11h), phase formation kinetics are enhanced, leading to stronger surface hardening and, consequently, improved tribological performance [10,18].

Tribological tests conducted under dry sliding conditions demonstrate a significant effect of ion nitriding parameters on the coefficient of friction and wear behavior of the investigated steel (Figure 3).

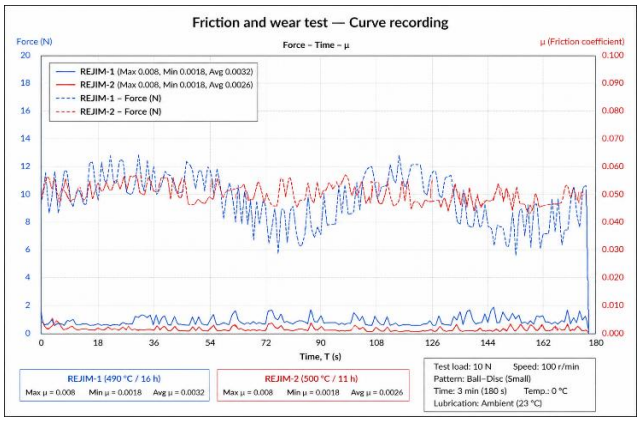

Fig. 3. Variation of the coefficient of friction (μ) as a function of time under dry sliding conditions for ion-nitrided 1.2343 tool steel: comparison between the regimes 490°C/16 h and 500°C/11 h.

As shown in the presented curves, the coefficient of friction exhibits relatively stable behavior over time for both regimes, while lower values and reduced fluctuation amplitude are observed for the 500°C/11h regime, indicating a more stable tribological contact. The average values of the coefficient of friction are $\mu \approx 0.0032$ for the 490°C/16h regime and $\mu \approx 0.0026$ for the 500°C/11h regime, with the lower value for the latter indicating more favorable tribological performance. The low values of the coefficient of friction are directly related to the enhanced wear resistance achieved through the formation of a diffusion layer enriched with fine nitrides of alloying elements (Cr, Mo, and V). These nitrides significantly contribute to increased hardness and resistance to plastic deformation in the contact zone, thereby limiting the development of adhesive and abrasive wear mechanisms [18,21,22]. For the 490°C/16h regime, a deeper diffusion layer is formed, providing a more uniform distribution of mechanical properties in depth. This results in improved load-bearing capacity and more stable behavior under prolonged loading, as stresses are distributed over a larger material volume. Such a structure is characterized by higher resistance to friction fatigue and a lower tendency toward localized wear [18,23]. In contrast, the 500°C/11h regime results in higher surface hardness, leading to a lower coefficient of friction and reduced intensity of adhesive wear. The increased hardness reduces the real contact area and, consequently, the adhesion forces between the contacting surfaces, which is consistent with literature data [21,22]. For both regimes, the absence of a compound (white) layer plays a significant role in wear behavior. Although this layer may exhibit high hardness, it is typically characterized by increased brittleness and a tendency for crack initiation and propagation, leading to localized material removal under loading. Its absence promotes better adhesion between the surface layer and the substrate, resulting in more stable wear behavior without abrupt surface degradation [17,21]. During tribological testing, the formation of a thin transfer layer is also possible, acting as a solid lubricating film and contributing to the reduction of friction and wear, which is typical for

nitrided steels [22]. The comparison of the results (Figure 3) shows that wear behavior is governed by different factors for the two regimes: at 490°C, the dominant factor is the deeper and more uniform diffusion layer, while at 500°C, the higher surface hardness plays the leading role. As a result, the 500°C/11h regime provides the best combination of low friction coefficient and high wear resistance, whereas the 490°C/16h regime ensures greater diffusion layer depth and a more gradual variation of properties in depth.

IV. CONCLUSIONS

Based on the conducted experimental investigations on ion nitriding of tool steel 1.2343, it can be concluded that for both applied regimes (490°C/16h and 500°C/11h), a clearly defined diffusion layer is formed without the presence of a compound (white) layer.

For the 490°C/16h regime, a deeper and more uniform diffusion layer with a thickness of approximately 250 µm is formed, characterized by a gradual hardness variation in depth and good load-bearing capacity. In contrast, the 500°C/11h regime leads to higher surface hardness, reaching values of up to approximately 698 $HV_{0.1}$, accompanied by a more pronounced decrease in hardness with increasing depth, indicating more intensive surface hardening.

The tribological investigations reveal very low values of the coefficient of friction for both regimes, with the lowest average value ($\mu \approx 0.0026$) obtained for the 500°C/11h regime. This behavior is associated with the formation of a diffusion layer enriched with alloy nitrides, which increase hardness, limit plastic deformation, and suppress adhesive and abrasive wear mechanisms.

A comparison of the results indicates that the 500°C/11h regime provides the best combination of high surface hardness and low coefficient of friction, whereas the 490°C/16h regime is characterized by a deeper and more uniform diffusion layer with improved load-bearing capacity. The obtained results demonstrate that optimization of ion nitriding parameters enables significant improvement of the surface properties of hot-work tool steels and represents an effective approach for enhancing their service performance.

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