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Research Article

Modeling and Experimental Analysis of Bias Voltage Effects on Hardness and Thickness of TiN Coatings Produced by PVD Process

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ABSTRACT

This study examines the impact of bias voltage on the mechanical properties and film thickness of TiN coatings deposited on cold work tool steel via the PVD process. TiN coatings, known for their excellent hardness and wear resistance, were deposited at varying bias voltages (100–300 V). Hardness measurements and SEM analyses were conducted to evaluate the relationship between bias voltage, hardness, and film thickness. Theoretical models, including hardness-load and indentation hardness relationships, were developed to provide a comprehensive understanding of these trends. The results demonstrate that increasing the bias voltage enhances coating hardness up to 250 V due to improved atomic mobility and nucleation density. However, beyond this threshold, grain coarsening and defect formation contribute to a reduction in hardness. A monotonic decrease in film thickness was observed with higher bias voltages, attributed to ion bombardment and re-sputtering effects. The developed models showed strong alignment with experimental results, particularly for indentation hardness behavior, while discrepancies in the hardness-load relationship were noted under high loads and higher bias voltages. These findings underscore the importance of precise bias voltage control and theoretical modeling in enhancing TiN coating performance for industrial applications.

1. Introduction

High-speed steels (HSS) are widely used in industrial applications due to their excellent thermal stability, durability, wear resistance, and resistance to chemical interactions. However, during drilling operations, chip formation and its impact on the drill surface negatively affect the performance of HSS tools. To address these issues, HSS tools are often enhanced with coatings such as TiN, TiCN, and CrN to improve their wear resistance and overall performance [1, 2].

Physical Vapor Deposition (PVD) technology is commonly used for coating HSS tools due to its low processing temperatures and environmentally friendly nature. TiN coatings are preferred for their high hardness and low friction coefficients. Studies have shown that PVD coatings such as TiN, Ti(Y)N, and TiAlN significantly enhance the mechanical properties of HSS tools, leading to improved performance in various machining applications [3, 4]. For instance, the addition of yttrium to TiN coatings (Ti(Y)N) increases adhesion and corrosion resistance, providing a 36% increase in tool life compared to standard TiN coatings [5].

Further studies have explored the impact of coating parameters such as cathode current and bias voltage on film thickness and hardness. Higher bias voltages increase ion bombardment, producing denser and harder coatings, while increased cathode currents enhance deposition rates and influence microstructure [6]. Additionally, duplex coatings, which combine nitriding and PVD coatings, offer the advantages of both methods, extending tool life and increasing wear resistance [7-9].

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Cold work tool steels are frequently used in applications requiring high wear resistance and hardness due to their high carbon and chromium content. For example, it has been reported that PVD coatings, including TiN, on DIN 1.2379 and 1.2080 steels significantly improve tool life and mechanical performance [1, 2]. Recent studies have further expanded the understanding of TiN coatings in various industrial applications. For instance, researchers have studied the tribological optimization of titanium-based PVD multilayer hard coatings on steels used for cold rolling applications, highlighting the critical role of deposition parameters in enhancing wear resistance and mechanical performance [10].

Similarly, the wear behavior of uncoated, TiN, and AlTiN coated cold work tool steel (1.2379) was optimized using response surface methodology, providing valuable insights into how coating compositions influence durability under operational conditions [11]. Additionally, the mechanical behavior of PVD coatings during manufacturing processes was investigated, emphasizing the significance of coating-substrate interactions in determining overall performance [12]. These studies underline the continuous advancements in PVD coating technologies and the growing emphasis on optimizing mechanical properties through controlled deposition parameters.

Previous studies have extensively examined the relationship between coating thickness and hardness for PVD-deposited TiN coatings, highlighting the critical role of deposition parameters such as bias voltage. However, this study uniquely combines experimental findings with theoretical modeling approaches, including energy-based ion bombardment modeling and static/dynamic analysis methods. By integrating hardness and indentation models, this research offers a comprehensive understanding of the effects of bias voltage on both mechanical properties and indentation behavior, offering new insights into the optimization of PVD coatings for industrial applications [13–18].
Similarly, the wear behavior of uncoated, TiN, and AlTiN coated cold work tool steel (1.2379) was optimized using response surface methodology, providing valuable insights into how coating compositions influence durability under operational conditions [19, 20]. Additionally, the mechanical behavior of PVD coatings during manufacturing processes was investigated, emphasizing the significance of coating-substrate interactions in determining overall performance [21, 22]. Studies have demonstrated that PVD coatings such as TiN and AlTiN exhibit improved wear resistance due to optimized deposition conditions and substrate interactions [23, 24]. Furthermore, advancements in coating techniques have led to the development of enhanced tribological performance, particularly in cold rolling applications where surface integrity is crucial [25-27]. These studies underline the continuous advancements in PVD coating technologies and the growing emphasis on optimizing mechanical properties through controlled deposition parameters.

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2. Materials and Methods

2.1. Materials

The substrate material used for the coating process was 1.2080 (D3 AISI/SAE) Böhler-Edelstahl cold work tool steel Disc-shaped samples were cleaned using a KLN ultrasonic cleaner operating at a frequency of 40 kHz. The cleaning process was performed in deionized water at room temperature for 15 minutes to effectively remove surface contaminants. After ultrasonic cleaning, the samples were dried using clean, pressurized air to prevent any residual moisture. TiN coatings were deposited using a Multiarc (US.A.) and Siemens (Germany) PVD coating system at OPAŞ-Titanit Coatings Center. The coating parameters, including the applied bias voltages, are presented in Table 1.

2.2. Hardness measurements

Hardness measurements were performed using a Fischerscope microindentation hardness tester. The tests utilized a four-sided pyramidal (Vickers) diamond tip, which was brought into contact with the sample surfaces under fixed loading rates. The residual indent areas were measured after a constant loading period to calculate hardness values.

The bias voltage range of 100 V to 300 V was selected based on preliminary experimental observations and insights from previous studies on TiN coatings deposited via the PVD process. This range was chosen to cover both low and high bias conditions to observe the transition in coating properties. Lower bias voltages (100–150 V) were included to evaluate the initial stages of ion bombardment and its effect on coating density and hardness, while higher voltages (200–300 V) were selected to investigate potential grain coarsening, defect formation, and changes in mechanical properties due to increased ion energy [6, 9, 14].

The optimal performance observed at 250 V is attributed to enhanced atomic mobility and increased nucleation density, which significantly improved hardness and coating uniformity. This voltage represents a threshold where the beneficial effects of ion bombardment are maximized without inducing excessive defects or grain coarsening, as supported by similar findings in prior research [13, 23, 24].

The indentation depth range was between 0.05 to 2.85 μm. Additionally, we clarified that each hardness measurement was averaged from five replicates to ensure data reliability and consistency.

Table 1. Coating parameters

Bias Voltage (V)	Cathode Current (A)	Press (mTorr)	Coating Duration (min.)	Coating Temp. (°C)
100	50	2.1×10^{-2}	45	450
150	50	2.1×10^{-2}	45	450
200	50	2.1×10^{-2}	45	450
250	50	2.1×10^{-2}	45	450
300	50	2.1×10^{-2}	45	450

2.3. Film thickness measurement

Cross-secitonal scanning electron microscope (SEM) images were captured using a JEOL JSM 840 microscope at the Brisa R&D Center analytical laboratories. Film thicknesses were measured from cross-sectional SEM images at 3000× magnification under a 15 kV accelerating voltage.

2.4. Modeling approaches

2.4.1. Indentation hardness model

The indentation hardness H_{meas} was modeled based on the composite hardness approach commonly used in thin-film mechanics [10, 11].

The hardness at various indentation depths was modeled using the following equation:

$$H_{meas} = \left(H_{coat} \cdot (1 - f)\right) + (H_{subs} \cdot f) \qquad (1)$$

Where; H_{meas}: Measured hardness (theoretical, based on the model),

H_{coat}; Coating hardness, H_{subs}: Substrate hardness, $f = \frac{d}{d+t}$: with d as the indentation depth and t as the coating thickness.

2.4.2. Hardness-load relationship model

The load-dependent hardness model (H_{load}) follows methodologies proposed for analyzing mechanical properties of thin films under varying loads [10, 12, 13].

The hardness-load relationship was evaluated using the following expression:

$$H_{load} = \left(H_{coat} \cdot \left(1 - \frac{P}{P_{\max}}\right)\right) + \left(H_{subs} \cdot \frac{P}{P_{\max}}\right) \tag{2}$$

where; H_{load}:Load-dependent hardness (theoretical, based on the model),

P_{max}: Maximum load,
$H_{coating}$: Coating hardness,
$H_{substrate}$: Substrate hardness.

2.4.3. Energy-based ion bombardment model

To analyze the effects of bias voltage on coating properties, the energy-based ion bombardment model was employed [14, 15]. This model calculates the energy imparted to the coating surface using the equation:

$$E = \frac{1}{2}mv^2 \tag{3}$$

Where; m is the ion mass [14], and *v* represents the ion velocity derived from the applied bias voltage [15]. These high-energy ions significantly influence coating density, hardness, and re-sputtering effects.
The ion velocity (*v*) is calculated based on the applied bias voltage, using:

$$v = \sqrt{\frac{2qV}{m}} \tag{4}$$

Where; *q* is the ionic charge, *V* is the applied bias voltage, and *m* is the mass of the ion (e.g., titanium or nitrogen ions in this study) [16].

This modeling approach has been previously used in similar studies to explain the effects of ion bombardment on film growth and mechanical properties. For instance, studies have shown that energy transfer mechanisms during ion bombardment enhance surface diffusion and grain refinement [14, 15].

3. Results and Discussion

Hardness measurements of TiN-coated samples were carried out using a Fischerscope micro indentation hardness tester under the coating parameters listed in Table 1. The results for hardness-load and hardness-indentation depth relationships are presented in Figures 1 and 2. The initial observations indicate a significant dependence of the hardness values on the applied bias voltage during the coating process.

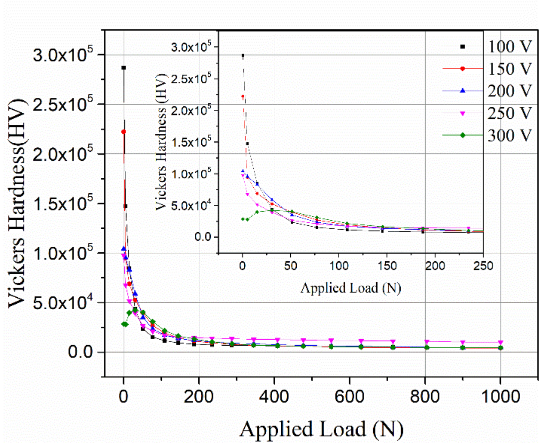

Figure 1. Variation of Vickers hardness of TiN-coated samples as a function of applied load for different bias voltages (100–300 V). The inset shows the detailed view for the load range 0–250 N.

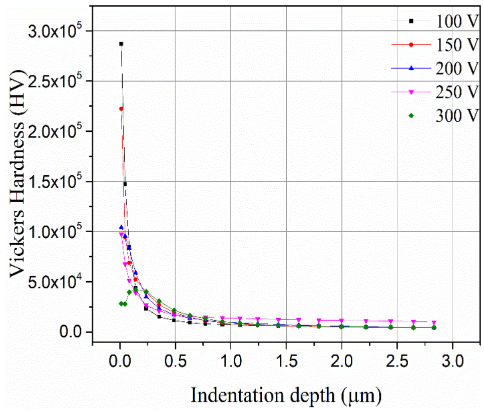

Figure 2. Variation of Vickers hardness of TiN-coated samples as a function of indentation depth

At low loading rates (<50 N), hardness values were high for coatings with low bias voltage. When the load amount increased up to 200 N, an increase in hardness values was observed in coatings with high bias voltage (Figure 1 inset). At loads above 200 N, the decrease in hardness values significantly slowed for all samples. After this load value, the hardness of the samples coated with a 200 and 250 V bias voltage was higher compared to the other samples.

Studies have shown that increasing the bias voltage generally leads to higher hardness values due to enhanced atomic mobility and compressive stress during the coating process [6, 12]. However, after reaching a certain threshold, further increases in bias voltage or coating current can result in grain coarsening and increased defects, which may reduce hardness and wear resistance [1, 3, 14]. Researchers have observed that while bias voltages around 100 V can significantly improve the mechanical properties of TiN coatings, bias voltages beyond this level may lead to increased friction and reduced coating integrity due to structural changes such as grain coarsening or the formation of defects [3, 4, 17, 21, 22].

In this study, hardness values increased up to a bias voltage of 250 V; beyond this value, a significant decrease in hardness was observed. Similar threshold values have been reported in the literature for comparable bias voltages and loading rates [1, 9, 13, 23, 24]. After this voltage value, the decrease in hardness was associated with grain size and defect formation in the coating [1]. The slight decrease or stabilization of hardness values after a loading rate of 200 N was also linked to defect formation in the coating as the bias voltage increased [9].

The observed trend of increasing hardness up to 250 V, followed by a subsequent decrease, aligns with findings from previous studies [26, 27]. Carabillò et al. [26] and Bülbül et al. [27] also reported that increasing bias voltage enhances hardness due to increased atomic mobility and compressive stress. However, beyond a certain threshold, grain coarsening and defect formation become dominant, leading to a decline in hardness. These discrepancies are often attributed to changes in coating microstructure, residual stress accumulation, and the influence of substrate interactions under higher bias voltages.

Additionally, it is important to explain the relationship between indentation depth and film thickness with hardness, which forms the basis of this study. A similar behavior observed in the hardness-bias voltage relationship was also evident in the hardness-indentation relationship (Figure 2). Up to an indentation depth of 0.15 micrometers, hardness values were directly proportional to the bias voltage. Higher hardness values were observed at higher bias voltage levels.

Between indentation depths of 0.15 and 0.7 micrometers, the sample coated at a bias voltage of 300 V exhibited the highest hardness value. However, beyond 0.7 micrometers, a trend similar to that observed in the hardness-bias voltage relationship emerged, where the sample coated at 250 V demonstrated the highest hardness. These findings highlight the transition from coating-dominated hardness behavior at lower indentation depths to substrate-dominated behavior as the indentation depth increased.

These transitions have been extensively studied, highlighting the relationship between coating thickness, mechanical properties, and the effects of deposition parameters and substrate interactions. [12-14].

Figure 3 illustrates the thickness of the TiN coatings. The film thicknesses were determined by averaging multiple measurements obtained from SEM cross-sectional images using screen scale calibration. The results are presented in Table 2, showing the variation of coating thickness with respect to bias voltage.

Table 2. Film thickness of TiN coatings under varying bias voltages

Bias Voltage(V)	**Thickness(µm)**
100	1.64
150	1.55
200	1.47
250	1.03
300	0.9

The data indicate a monotonic decrease in film thickness as bias voltage increases. This observation aligns with previous studies that attribute the reduction in thickness to ion bombardment effects, which lead to resputtering of surface atoms and reduced deposition rates at higher bias voltages [6, 16, 17]. Furthermore, the observed monotonic decrease in film thickness with increasing bias voltage aligns with the findings of in the study, which was reported similar trends in titanium-based PVD multilayer hard coatings [26].

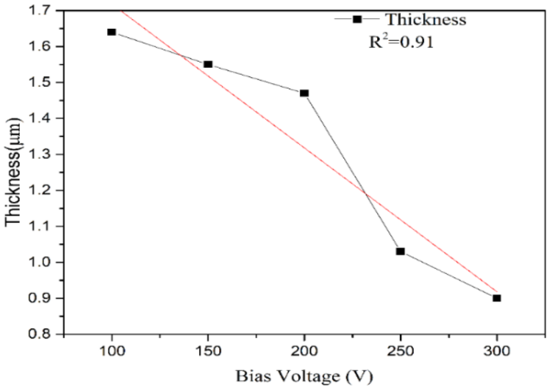

Figure 3. Film thickness of TiN coated samples with respect to Bias Voltage

Additionally, It was emphasized that deposition parameters, particularly bias voltage, significantly influence the wear behavior of TiN coatings, corroborating the hardness variations observed in this study [27]. It was further highlighted how substrate interactions under varying coating conditions affect mechanical properties, which parallels the substrate influence identified in our indentation hardness analysis [28].

This trend is accompanied by a rise in hardness values up to a certain threshold. The thickness reduction is monotonic up to a bias voltage of 200 V; however, a sharper decline is observed for coatings prepared at 250 V and 300 V. These observations align with findings from earlier studies, which reported similar behavior under varying bias voltage conditions [5, 6, 7, 16, 17].

The decrease in coating thickness with higher bias voltages is primarily attributed to the energy delivered by high-energy ions during deposition. These ions strike the coating surface, leading to re-evaporation or resputtering of surface atoms. This phenomenon slows down the growth rate of the coating and results in a thinner, denser structure. Ion bombardment plays a critical role in determining the coating's microstructure. The resputtering effect induced by high-energy ions can refine grain structures by promoting densification but also introduces defects such as voids or microcracks when the ion energy exceeds optimal levels. This process alters grain size distribution, contributing to hardness variations. Additionally, pseudo-diffusion layers formed due to ion bombardment can affect coating thickness and mechanical properties. In this study, SEM cross-sectional analysis was employed to qualitatively assess coating thickness and structural uniformity.

However, quantitative analysis of pseudo-diffusion effects was not performed due to the limitations of the available data. Future studies incorporating advanced characterization techniques such as EDX or TEM could provide deeper insights into these effects. The energy-based ion bombardment model, as discussed earlier, supports this explanation by demonstrating how higher ion energies disrupt coating growth dynamics [18]. While the energy-based ion bombardment model provides a robust framework for understanding the effects of bias voltage on coating properties, the energy calculations could be further supported by comparative studies.

Incorporating references related to ion energy distribution and its impact on microstructural evolution in TiN coatings would strengthen the model's validity. Future studies could enhance this model by integrating experimental data on ion flux density and energy transfer efficiency during the PVD process, allowing for more precise predictions of coating behavior under varying deposition conditions. Additionally, coatings deposited at higher bias voltages exhibit enhanced grain refinement, contributing to their increased hardness and density despite reduced thickness.

Energetic particles directed towards the substrate surface deposit a portion of their energy through inelastic collisions, leading to localized heating of the substrate surface. This heating plays a critical role in surface diffusion and determines the composition and structure of the formed coating. Impurity atoms, such as embedded carbon or oxygen in the recoil surface region, can form a pseudo-diffusion layer that affects coating thickness. When the energy of the particles is sufficiently high, these impurities are sputtered before the pseudo-diffusion layer can form, resulting in thinner and harder coatings [6, 15, 20].

Continued ion bombardment enhances physical mixing, diffusion, and nucleation modes while removing unbound atoms from the surface, thus improving the surface quality. High-energy impacts also restrict the mobility of condensing atoms on the surface, increasing nucleation density. Coatings deposited at bias voltages exceeding 200 V typically exhibit higher nucleation densities, which correlate with enhanced hardness and refined microstructures [7, 9, 12, 25].

Studies have demonstrated that higher substrate temperatures, induced by energetic particle impacts, facilitate diffusion processes, promote uniform coating, and enhance hardness properties. PVD coatings, such as TiN, processed under controlled high-temperature conditions, show increased hardness and reduced defects [10, 16]. Moreover, it has been reported that pseudo-diffusion layers formed by trapped impurities can alter both coating thickness and hardness.

High-energy particle impacts effectively sputter these impurities, leading to coatings with superior mechanical and tribological properties, as well as reduced surface roughness [5, 6, 17]. Many researchers have reported similar results on film thickness and hardnes affected by substrate temperature and nucleation formation. Higher substrate temperatures facilitate the diffusion process, promoting uniform coating and enhancing hardness properties. They observed that PVD coatings like TiN exhibit increased hardness when processed under controlled high-temperature conditions [7, 18, 19].

Figures 4–8 show the cross-sectional SEM images of the samples, highlighting the structural differences and coating integrity at varying bias voltages. The microstructural evolution of TiN coatings with increasing bias voltage is summarized in Table 3. At lower bias voltages (100–150 V), the coatings exhibit a fine-grained, dense structure with minimal defects. As the bias voltage increases beyond 200 V, grain coarsening becomes evident, and minor porosity is observed. The highest bias voltage (300 V) results in a rougher morphology with visible cracks, indicating a potential increase in internal stress. These observations emphasize the influence of bias voltage on coating microstructure and mechanical stability.

Table 3. The microstructural evolution of TiN coatings with increasing bias voltage and film thicness

Bias Voltage (V)	Grain structure	Thickness (μm)	Observed defects
100	Fine grains	1.64	None
150	Dense structure	1.55	Minor voids
200	Dense structure	1.47	Slightly porosity
250	Coarse grains	1.03	Voids&microcracks
300	Coarse grains	0.90	Cracks observed

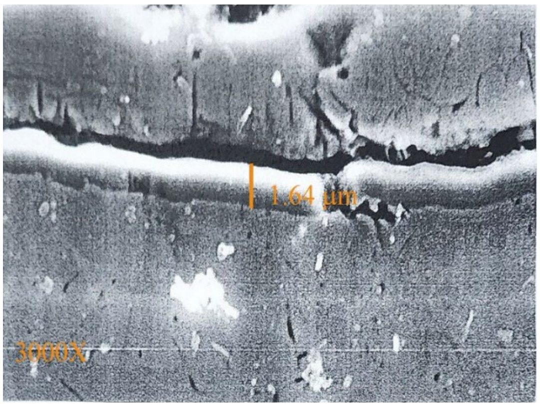

Figure 4. SEM cross-section of TiN coating deposited at 100 V bias voltage, indicating the measured coating thickness (1.64 μm) and its interface with the substrate

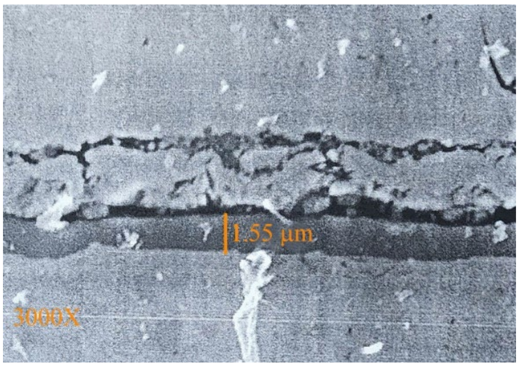

Figure 5. SEM cross-section of TiN coating deposited at 150 V bias voltage, indicating the measured coating thickness (1.55 μm) and its interface with the substrate

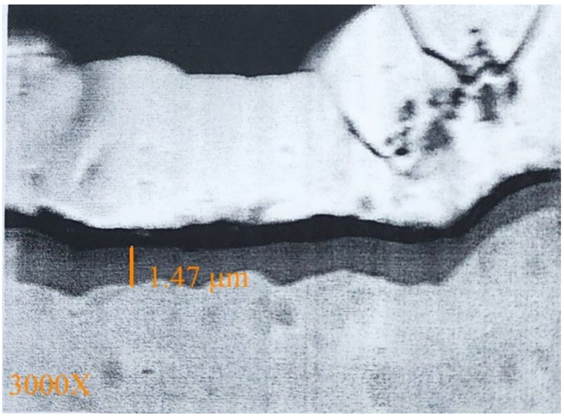

Figure 6. SEM cross-section of TiN coating deposited at 200 V bias voltage, indicating the measured coating thickness (1.47 μm) and its interface with the substrate

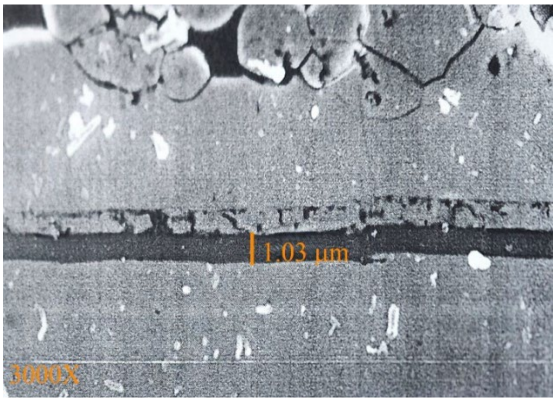

Figure 7. SEM cross-section of TiN coating deposited at 250 V bias voltage, indicating the measured coating thickness (1.03 μm) and its interface with the substrate

The revised hardness-load model shows a strong correlation with experimental data across all bias voltages, demonstrating its robustness in capturing the mechanical behavior of TiN coatings. As illustrated in Figure 9, the experimental hardness values (represented by the straight lines) closely follow the calculated model predictions (dashed lines), particularly at lower loads.

However, for coatings prepared with bias voltages above 150 V and under high loads (>200 N), minor deviations persist. These small differences are likely due to increased substrate influence as indentation depth surpasses the coating thickness, leading to an overestimation of hardness values at high loads. This effect is well-documented in literature and is an inherent limitation of simplified hardness models that do not fully account for layered elastic-plastic interactions. Future improvements could involve a more advanced layered mechanical model that explicitly incorporates substrate effects, as well as alternative indentation analysis methods such as the Oliver-Pharr approach for nanoindentation. Despite these minor deviations, the model provides a reliable framework for understanding the hardness-load relationship in TiN coatings. The findings of this study indicate that at high loads exceeding 200 N, particularly for coatings deposited at bias voltages above 150 V, slight deviations between the experimental hardness values and the predictions of the hardness-load model are observed.

These discrepancies are primarily due to the increasing influence of the substrate as the indentation depth becomes comparable to or exceeds the coating thickness.

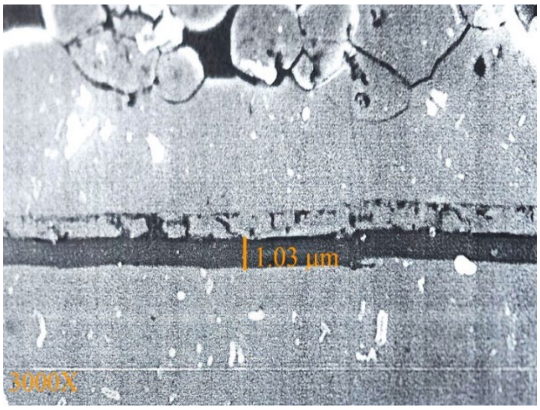

Figure 8. SEM cross-section of TiN coating deposited at 300 V bias voltage, indicating the measured coating thickness (0.90 μm) and its interface with the substrate

While the model remains highly effective in representing the overall hardness-load relationship, these observations emphasize the importance of incorporating substrate effects in mechanical property evaluations, especially for thin coatings.

Additionally, ensuring precise measurement and control of coating thickness before hardness testing could further improve the accuracy and reliability of mechanical property assessments

The examination of the hardness-indentation depth relationship reveals a strong correlation between the experimental data and the theoretical model predictions across all bias voltage levels and indentation depths (Figure 10). This agreement suggests that the indentation hardness model effectively captures the localized mechanical behavior of the coatings, including the transition from coating-dominated to substrate-influenced regions.

While minor deviations can occur due to localized microstructural variations, the indentation model demonstrates a consistent ability to represent hardness behavior across different conditions. Compared to the hardness-load relationship, where substrate influence becomes more significant at higher loads, indentation hardness measurements provide a more localized assessment, making them less susceptible to macroscopic factors such as substrate effects or inhomogeneities.

Additionally, the robustness of the indentation model is supported by its dependence on well-characterized parameters such as coating thickness and indentation depth, further reinforcing its reliability in mechanical property evaluations. These findings emphasize the importance of precise modeling in understanding thin-film mechanics while also acknowledging the inherent differences between various hardness measurement methodologies.

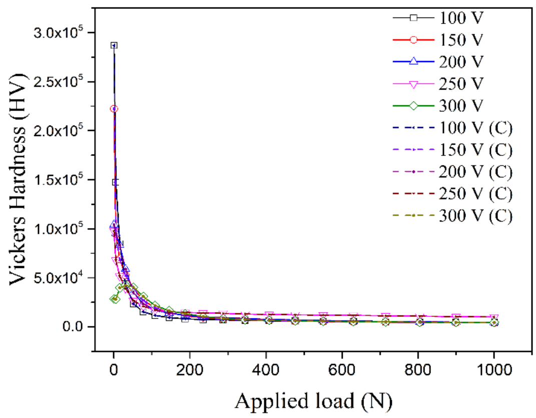

Figure 9. Variation of Vickers hardness of TiN-coated samples as a function of applied load (straight line: experimental, dashed line: calculated)

The calculated model exhibits a strong correlation with the experimental trend at low to moderate loads, accurately capturing the coating-dominated behavior. At higher loads (>200 N), minor deviations are observed, which can be attributed to the increasing influence of the substrate and potential microstructural variations such as grain coarsening. These variations, which lead to a maximum discrepancy of approximately 0.3%, are consistent with findings from previous

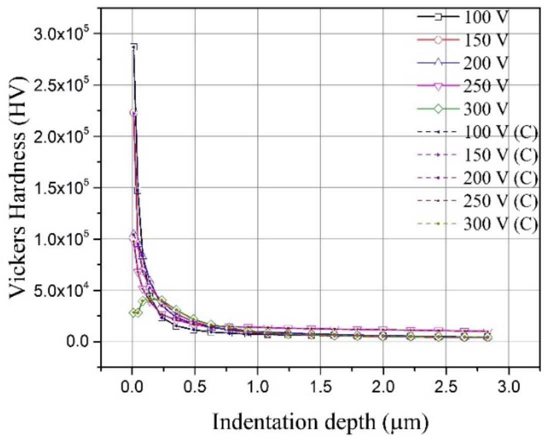

Figure 10. Variation of Vickers hardness of TiN-coated samples as a function of indentation depth (straight line: experimental, dashed line: calculated)

microindentation studies [29, 30]. While such discrepancies are inherent in thin-film mechanical characterization, they highlight the importance of considering substrate effects and material heterogeneities in hardness modeling.

Unlike the hardness-load relationship, where macroscopic factors and substrate contributions introduce variability, the indentation model provides a robust framework for evaluating the intrinsic properties of thin coatings. These findings emphasize the importance of utilizing multiple models to capture different aspects of mechanical behavior comprehensively.

The observed trends in hardness and film thickness with varying bias voltages highlight the significant influence of deposition parameters on the mechanical properties of TiN coatings. The monotonic decrease in film thickness with increasing bias voltage is consistent with ion bombardment effects, leading to re-sputtering and reduced growth rates. Additionally, the enhanced hardness observed up to 250 V bias voltage can be attributed to increased atomic mobility and nucleation density, while the decline beyond this threshold is likely due to grain coarsening and defect formation. These results align with previous studies, confirming the complex interplay between coating parameters and mechanical behavior.

4. Conclusion

This study systematically investigated the influence of bias voltage on the mechanical properties and film thickness of TiN coatings deposited on cold work tool steel using the PVD process. The key findings and implications of this research are summarized as follows: A strong correlation between bias voltage and coating properties was observed, with optimal mechanical performance achieved at a bias voltage of 250 V. This bias voltage facilitated enhanced atomic mobility and nucleation density, resulting in coatings with improved hardness and structural integrity.

Film thickness decreased monotonically with increasing bias voltage, consistent with the predictions of the energy-based ion bombardment model. The reduction in coating thickness at higher bias voltages was attributed to resputtering effects caused by ion bombardment, which also contributed to refined microstructures and increased hardness. The hardness-indentation relationship exhibited excellent agreement between experimental data and theoretical model predictions across all bias voltage levels. This finding underscores the robustness of the indentation hardness model in capturing localized mechanical behavior and transitions between coating-dominated and substrate-influenced regimes. Slight deviation between experimental data and model predictions were observed in the hardness-load relationship for coatings prepared at bias voltages above 150 V under high loads (>200 N). These deviations were primarily attributed to the increased contribution of substrate effects as the indentation depth approached or exceeded the coating thickness.

These findings underscore the potential of TiN coatings to enhance tool life and improve wear resistance in industrial applications. The optimal control of deposition parameters, particularly bias voltage, is critical for tailoring coatings to specific performance requirements. The study highlights the importance of combining experimental measurements with theoretical models to gain a comprehensive understanding of thin film behavior.

To address the limitations identified in this study, future research should focus on: Refining the hardness-load model to better account for substrate effects and high-load scenarios. Integrating precise coating thickness measurements prior to hardness evaluations to enhance the reliability of experimental data. Exploring advanced ion bombardment models to further understand the interplay between deposition parameters, coating microstructure, and mechanical performance.

Future research could expand on the findings of this study by exploring different PVD coating compositions, such as TiAlN and TiCN, under similar bias voltage conditions to evaluate their mechanical and tribological properties. Additionally, investigating the effects of deposition temperature on coating hardness, microstructure, and adhesion could provide deeper insights into the thermal dynamics of the PVD process. Furthermore, evaluating the tribological performance of TiN coatings in real-world applications, such as machining and cutting tools, would help bridge the gap between laboratory-scale studies and industrial applications. These future studies will contribute to a more comprehensive understanding of the interplay between deposition parameters and coating performance. In summary, this study offers valuable insights into the mechanical behavior of TiN coatings and emphasizes the potential of PVD coatings to enhance tool life and wear resistance in industrial applications.

Article Information Form

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The Declaration of Conflict of Interest/ Common Interest

No conflict of interest or common interest has been declared by the author.

The Declaration of Ethics Committee Approval

This study does not require ethics committee permission or any special permission.

The Declaration of Research and Publication Ethics

The author of the paper declare that they comply with the scientific, ethical and quotation rules of SAUJS in all processes of the paper and that they do not make any falsification on the data collected. In addition, they declare that Sakarya University Journal of Science and its editorial board have no responsibility for any ethical violations that may be encountered, and that this study has not been evaluated in any academic publication environment other than Sakarya University Journal of Science.

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