

Effect of Substrate Heat Treatment on the Tribological Performance of MoS_2 +Ni and DLC Coatings Deposited on Tool Steels

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1 Introduction

Tool steels employed in plastic injection molds and forming tools are continuously exposed to severe tribological conditions involving friction, wear, cyclic loading, and adhesive interactions(Funazuka et al. 2022) (Liu et al. 2026) (X. Wang et al. 2022). These phenomena promote surface degradation, dimensional inaccuracies, and premature tool failure, generating significant economic losses in manufacturing industries. Consequently, surface engineering techniques have become essential for improving the service life and reliability of tooling components. (Barba et al. 2024; Lijun Wang et al. 2022; Zia 2025)

Among the available surface modification technologies, diamond-like carbon (DLC) coatings have emerged as one of the most promising solutions due to their unique combination of high hardness, low friction coefficient, chemical inertness, and excellent wear resistance. Recent investigations have demonstrated that DLC coatings can significantly reduce friction and improve the tribological performance of tool steels under both dry and lubricated operating conditions (Khun et al. 2024; Kovacı et al. 2018; Efeoglu et al. 2024; Funazuka et al. 2022; Hua et al. 2025). Furthermore, advances in deposition techniques and coating architectures have enabled the development of DLC systems with improved adhesion, mechanical stability, and resistance to severe contact conditions (Łępicka et al. 2017; Lijun Wang et al. 2022; Zia 2025; Kapsiz et al. 2023).

Summary of recent studies on DLC and MoS_2 -based coatings deposited on tool steels and the research gap addressed in the present work.

Reference	Substrate	Coating/Treatment	Main findings
(Toboła et al. 2021)	Tool steel	DLC + surface pretreatment	Summary of recent studies on DLC and MoS_2 -based coatings deposited on tool steels and the research gap addressed in the present work.

Reference	Substrate	Coating/Treatment	Main findings
(Kovacı et al. 2018)	AISI 4140	DLC	Surface preparation improved adhesion and tribological performance. <i>Summary of recent studies on DLC and MoS₂-based coatings deposited on tool steels and the research gap addressed in the present work.</i>
(Ahmad et al. 2025)	Tool steel	DLC	Reduced friction and wear compared with uncoated steel <i>Summary of recent studies on DLC and MoS₂-based coatings deposited on tool steels and the research gap addressed in the present work.</i>
(Moreno-Barcenas et al. 2018)	M2 steel	Plasma nitriding + DLC	Improved anti-adhesive behavior during sheet forming. <i>Summary of recent studies on DLC and MoS₂-based coatings deposited on tool steels and the research gap addressed in the present work.</i>
(Zhou et al. 2025)	D2 steel	Duplex treatment + DLC	Improved coating adhesion and durability <i>Summary of recent studies on DLC and MoS₂-based coatings deposited on tool steels and the research gap addressed in the present work.</i>

Reference	Substrate	Coating/Treatment	Main findings
(Khan et al. 2025)	316L biomedical alloy	DLC	Significant improvement in wear resistance <i>Summary of recent studies on DLC and MoS₂-based coatings deposited on tool steels and the research gap addressed in the present work.</i> Reduced friction coefficient and Fretting
Present work	<i>Summary of recent studies on DLC and MoS₂-based coatings deposited on tool steels and the research gap addressed in the present work.</i> AISI P20+Ni AISI 420	DLC and MoS ₂ +N	<i>Summary of recent studies on DLC and MoS₂-based coatings deposited on tool steels and the research gap addressed in the present work.</i> Comparative evaluation of substrate treatment and coating type wear mechanics, hardness and tribological performance

Several authors have reported that the tribological behavior of DLC coatings is strongly influenced by substrate characteristics. Surface roughness, hardness, residual stresses, and pretreatment methods directly affect coating adhesion and wear performance (Tobola et al. 2021; Ramos et al. 2024; Zhu et al. 2026; L. Wang et al. 2022; Martins et al. 2021). In particular, duplex treatments combining thermochemical processes and DLC deposition have shown remarkable improvements in wear resistance and load-bearing capacity due to the synergistic interaction between the hardened substrate and the coating layer (Wang et al. 2026; Zhang et al. 2026; Luo et al. 2024; Neto et al. 2024; Libório et al. 2020; Xiao et al. 2022). Recent studies have demonstrated that nitrided or plasma-treated substrates promote enhanced adhesion and longer coating life compared with untreated steels (Liu et al. 2026; Cora and Koç 2009; Sahoo et al. 2022). In addition to DLC coatings, molybdenum disulfide (*MoS₂*)-based coatings have attracted considerable attention because of their excellent solid-lubrication properties. The lamellar structure of (*MoS₂*) facilitates easy

shear between atomic planes, resulting in low friction coefficients and reduced wear under sliding conditions. Several investigations have shown that MoS_2 coatings can effectively reduce friction in tooling applications, particularly when combined with metallic additions that improve coating toughness and adhesion (Neto et al. 2024; Zhu et al. 2026). Although DLC coatings generally exhibit superior hardness and wear resistance, (MoS_2)-based coatings remain attractive for applications where friction reduction is the primary requirement.

Despite the extensive literature on DLC-coated tool steels, most studies have focused on individual coating systems, specific substrate materials, or isolated surface treatments (Ahmad et al. 2025; Cora and Koç 2009; Neto et al. 2024; Luo et al. 2024; Khan et al. 2025; Zhang et al. 2026). Comparatively fewer investigations have evaluated the combined influence of substrate condition, thermochemical treatment, and coating type on the tribological performance of tool steels used in mold manufacturing. Furthermore, direct comparisons between DLC and MoS_2 +Ni coatings deposited on industrial mold steels such as AISI P20+Ni and AISI 420 modified steel remain scarce.

Therefore, the objective of this work is to evaluate the tribological performance of DLC and MoS_2 +Ni coatings deposited by magnetron sputtering on AISI P20+Ni and AISI 420 modified tool steels subjected to different substrate conditions, including untreated, quenched, Tenifer-treated, and quenched-plus-Tenifer-treated states. Tribological behavior was assessed through scratch testing, optical profilometry, scanning electron microscopy, and nanoindentation. Special attention was given to the influence of substrate treatment on scratch resistance, wear mechanisms, coating adhesion, hardness, and overall tribological performance.

As shown in Table 9, previous studies have primarily focused on DLC-coated tool steels and isolated surface treatments. However, a direct comparison between DLC and MoS_2 +Ni coatings deposited on AISI P20+Ni and AISI 420 steels subjected to quenching, Tenifer treatment, and combined treatments has not been reported. Therefore, the present work aims to fill this gap by systematically evaluating the influence of substrate condition and coating type on tribological performance.

2 Materials and Methods

The experimental investigation was carried out using two commercial tool steels commonly employed in the manufacture of plastic injection molds: AISI P20+Ni and AISI 420 modified stainless steel. These materials were selected because of their widespread industrial use and their distinct mechanical and tribological characteristics. AISI P20+Ni is a pre-hardened mold steel characterized by good toughness, dimensional stability, and machinability, whereas AISI 420 modified steel exhibits superior corrosion resistance and the ability to achieve high hardness after heat treatment. The nominal chemical compositions of both steels are presented in Table 10.

Nominal chemical composition of the investigated tool steels (wt. %)

Steel	C	Si	Mn	Cr	Ni	Mo	V	Fe
AISI P20+Ni	0.37	0.35	1.46	1.94	1.02	0.20	–	Balance
AISI 420 Mod	0.38	0.50	0.82	13.50	0.30	0.51	0.32	Balance

Prior to surface modification, all specimens were machined to the required dimensions and subjected to grinding and polishing operations in order to obtain a homogeneous surface finish. Subsequently, the samples were cleaned and degreased to eliminate contaminants that could adversely affect coating adhesion and the reproducibility of the tribological tests.

Four substrate conditions were evaluated throughout the study: untreated, quenched, Tenifer-treated, and quenched plus Tenifer-treated. The quenching treatment was applied to increase the hardness and load-bearing capacity of the substrates, promoting a more favorable support for the deposited coatings. The Tenifer thermochemical treatment was performed to generate a hardened diffusion layer enriched with nitrogen and carbon, which improves surface hardness, wear resistance, and fatigue performance. The combined quenching and Tenifer treatment was selected to evaluate the synergistic effect of bulk hardening and surface modification on the tribological behavior of the coating–substrate system. The processing parameters were selected according to industrial practice and the recommendations for each steel grade, ensuring reproducible treatment conditions and homogeneous surface properties.

Following the substrate treatments, two coating systems were deposited by magnetron sputtering: Diamond-Like Carbon (DLC) and MoS₂+Ni composite coatings. Prior to deposition, the specimens underwent an additional cleaning stage to remove any residual contaminants and to promote adequate coating adhesion. Magnetron sputtering was selected because it provides excellent control of coating composition, thickness, and microstructural uniformity while maintaining good adhesion to metallic substrates. DLC coatings were chosen due to their high hardness, low friction coefficient, and excellent wear resistance, whereas MoS₂+Ni coatings were selected because of their solid-lubrication capability and their potential to reduce friction under sliding conditions.

The tribological performance of the coated specimens was evaluated through progressive-load scratch testing. During the test, a diamond stylus was displaced across the coating surface while the applied load increased continuously. The resulting scratch tracks were used to assess coating adhesion, resistance to localized deformation, crack formation, and failure mechanisms. Scratch morphology and damage evolution were subsequently analyzed using optical and electron microscopy techniques.

Optical profilometry was employed to characterize the geometry of the scratch tracks and to determine the average scratch depth (PROM). These measurements provided quantitative information regarding the resistance of the coating–substrate systems to

mechanical damage. Scanning electron microscopy (SEM) was used to examine coating morphology, wear mechanisms, and failure modes, including cracking, delamination, plastic deformation, and material removal. In addition, nanoindentation tests were performed to determine hardness and elastic modulus values from load–displacement curves. The results obtained from scratch testing, profilometry, SEM observations, and nanoindentation were analyzed comparatively in order to establish the influence of substrate condition and coating type on the overall tribological performance of the investigated systems.

The coatings were deposited using a magnetron sputtering system under controlled vacuum conditions. Prior to deposition, all specimens were subjected to ultrasonic cleaning for 10 min and positioned at a target-to-substrate distance of 90 mm. Target conditioning was performed before each deposition process in order to remove surface contaminants and stabilize the sputtering conditions. For the MoS₂+Nb coating, Nb and MoS₂ targets were cleaned at 25 W for 2 min, whereas the DLC coating required Nb and carbon target cleaning at 50 W for 2 min. Plasma cleaning was subsequently carried out for 10 min to activate the substrate surface and improve coating adhesion. The plasma treatment was conducted at 150 W and 0.002 Torr for the MoS₂+Nb coatings and at 100 W and 0.002 Torr for the DLC coatings.

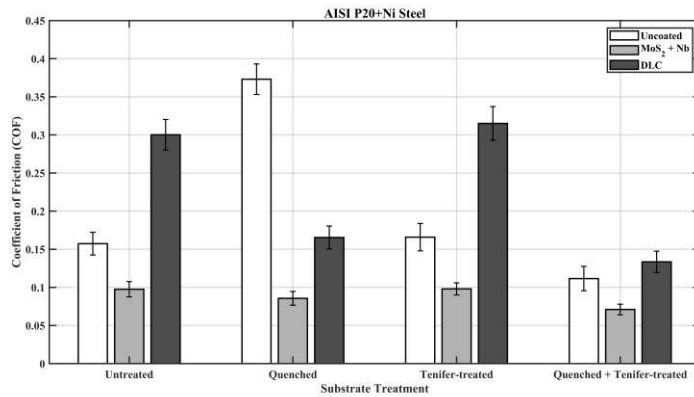
An intermediate Nb layer was deposited before the final coating deposition to improve adhesion between the substrate and the coating. For the MoS₂+Nb system, the interlayer was deposited at 150 W for 20 min under a pressure of 0.0005 Torr and a bias voltage of -75 V. In contrast, the DLC system employed a Nb interlayer deposited at 250 W for 10 min under the same pressure and bias conditions. The final MoS₂+Nb coating was produced using Nb and MoS₂ targets operating at 25 W and 75 W, respectively, for 60 min, whereas the DLC coating was deposited from a carbon target at 300 W for 10 min. In all cases, deposition was carried out at a pressure of 0.0005 Torr with a substrate bias of -75 V and continuous substrate rotation corresponding to an effective rotational speed of approximately 18.5 rpm. These deposition parameters were selected to obtain homogeneous coatings with adequate adhesion and tribological performance for subsequent characterization.

3 Results and discussion

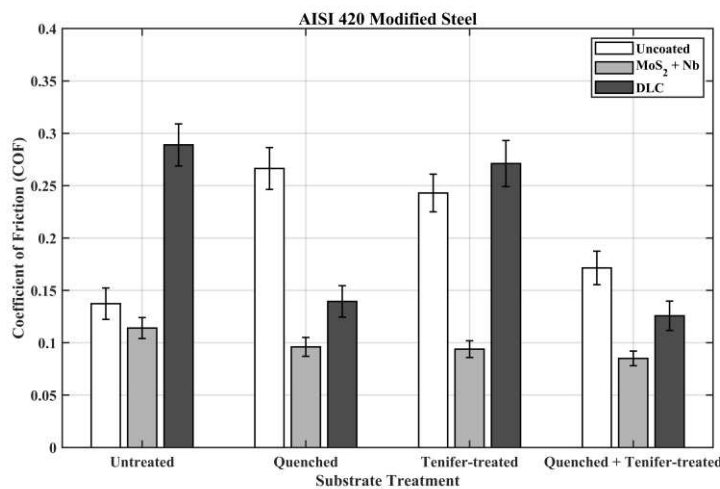
3.1 Effect of Substrate Treatment on the Coefficient of Friction

Figures 1 and 2 present the coefficient of friction (COF) obtained for the AISI P20+Ni and AISI 420 modified steels under different substrate conditions and coating systems. Significant variations were observed as a function of both the substrate treatment and the deposited coating, demonstrating the importance of substrate engineering in determining the overall tribological response.

For the untreated condition, the MoS₂+Nb coating exhibited the lowest friction coefficients in both steels, with values of 0.0976 and 0.1140 for AISI P20+Ni and AISI 420 modified steel, respectively. In contrast, the DLC coating produced substantially higher friction coefficients, reaching 0.3002 for AISI P20+Ni and 0.2889 for AISI 420 modified steel. These results indicate that under untreated substrate conditions the solid-lubricant effect provided by MoS₂ dominates the tribological response, resulting in a significant reduction in friction compared with both the uncoated substrates and the DLC-coated specimens.



Coefficient of friction (COF) of AISI P20+Ni steel as a function of substrate treatment and coating system. Error bars represent the standard deviation of the experimental measurements.



Coefficient of friction (COF) of AISI 420 modified steel as a function of substrate treatment and coating system. Error bars represent the standard deviation of the experimental measurements

After quenching treatment, a marked reduction in friction was observed for both coating systems. The MoS₂+Nb coating maintained the lowest COF values, decreasing to 0.0856 for AISI P20+Ni and 0.0961 for AISI 420 modified steel. A substantial reduction was also observed for the DLC coating, whose friction coefficient decreased by approximately 45% and 52% for AISI P20+Ni and AISI 420 modified steel, respectively, compared with the untreated condition. The improved performance is attributed to the increased substrate hardness and load-bearing capacity resulting from the quenching treatment, which reduced localized deformation during sliding.

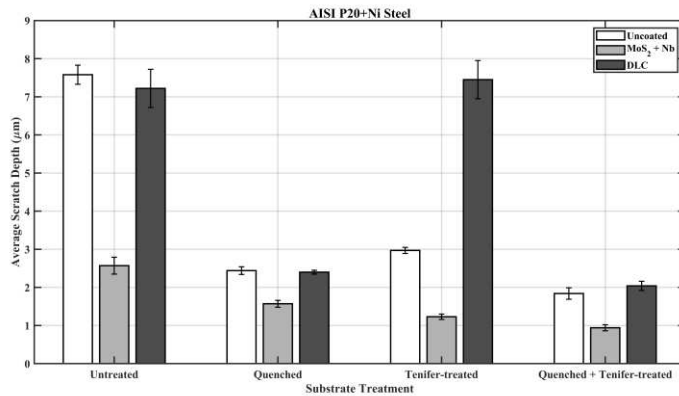
For the Tenifer-treated condition, the friction behavior differed depending on the coating system. The MoS₂+Nb coating continued to exhibit stable and low friction coefficients, remaining close to 0.10 for both steels. In contrast, the DLC-coated specimens showed a significant increase in friction compared with the quenched condition, reaching 0.3151 for AISI P20+Ni and 0.2711 for AISI 420 modified steel. This behavior suggests that although the Tenifer treatment improved surface hardness, the interaction between the DLC layer and the modified substrate may have altered the tribological contact conditions, resulting in higher friction during scratching.

The combined quenching and Tenifer treatment produced the most favorable tribological response. Under these conditions, the lowest friction coefficients of the entire study were obtained for the MoS₂+Nb coating, with values of 0.0710 for AISI P20+Ni and 0.0851 for AISI 420 modified steel. Similarly, the DLC coating exhibited its lowest friction coefficients, reaching 0.1335 and 0.1258, respectively. These results indicate a synergistic effect between bulk hardening and thermochemical surface modification, providing improved support for the deposited coatings and minimizing friction-related damage.

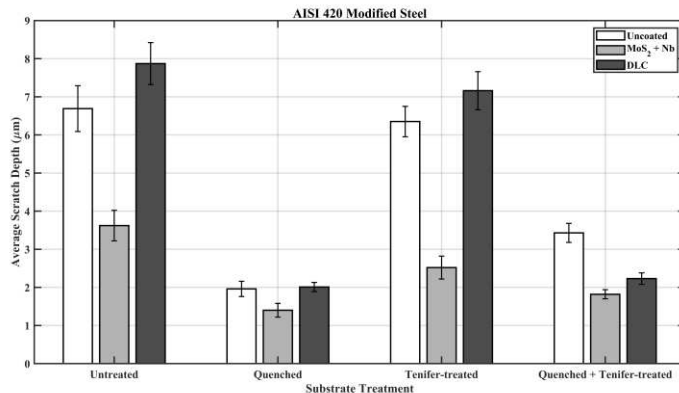
A comparison between both substrate materials reveals that AISI P20+Ni generally exhibited lower friction coefficients than AISI 420 modified steel for the MoS₂+Nb coating, particularly after the combined quenching and Tenifer treatment. Conversely, the DLC coating showed slightly better performance on AISI 420 modified steel under the heat-treated conditions. Nevertheless, the differences between the two steels were smaller than the variations induced by coating type and substrate treatment.

Overall, the results demonstrate that the coating composition was the dominant factor controlling friction behavior. MoS₂+Nb consistently provided the lowest coefficient of friction regardless of substrate condition, confirming the effectiveness of its solid-lubrication mechanism. Furthermore, the combination of quenching and Tenifer treatment enhanced the tribological performance of both coating systems by increasing substrate support and reducing friction-induced damage. Among all investigated configurations, the MoS₂+Nb coating deposited on quenched and Tenifer-treated AISI P20+Ni steel exhibited the most favorable tribological performance, achieving the lowest coefficient of friction and the highest stability during testing.

3.2 Effect of Substrate Treatment on Scratch Resistance



Average scratch depth (PROM) measured by optical profilometry for AISI P20+Ni steel as a function of substrate treatment and coating system.



Average scratch depth (PROM) measured by optical profilometry for AISI 420 modified steel as a function of substrate treatment and coating system.

For the AISI P20+Ni steel, the untreated condition exhibited relatively similar scratch depths for the uncoated substrate and the DLC coating, whereas the $\text{MoS}_2 + \text{Nb}$ coating significantly reduced the penetration depth. After quenching, a substantial improvement in scratch resistance was observed for both coating systems. The DLC coating reduced the average scratch depth by approximately 65% compared with the untreated condition, while the $\text{MoS}_2 + \text{Nb}$ coating achieved a reduction of nearly 52%. These results indicate that the increased substrate hardness provided by quenching enhanced the load-bearing capacity of the coating-substrate system and reduced localized deformation during scratching.

For the Tenifer-treated condition, the DLC-coated specimens exhibited scratch depths comparable to those measured in the untreated condition, suggesting that the thermochemical treatment alone did not significantly improve the resistance to penetration of the DLC system. In contrast, the $\text{MoS}_2 + \text{Nb}$ coating showed a reduction in scratch depth of approximately 50%, demonstrating that the Tenifer treatment was more

effective in supporting this coating system. When the substrate was subjected to the combined quenching and Tenifer treatment, all coating configurations exhibited lower scratch depths than those observed for the untreated condition. Nevertheless, the improvement was less pronounced than that obtained after quenching alone, indicating that the quenching treatment was the dominant factor controlling scratch resistance in AISI P20+Ni steel.

A similar trend was observed for the AISI 420 modified steel. The untreated condition exhibited the highest scratch depths for both the uncoated substrate and the DLC coating, while the MoS₂+Nb coating produced a moderate reduction in penetration depth. After quenching, a significant improvement in scratch resistance was obtained for all configurations, with reductions of approximately 70% and 60% for the uncoated and DLC-coated specimens, respectively. The MoS₂+Nb coating also showed improved performance, confirming the beneficial effect of substrate hardening. In contrast, the Tenifer-treated condition resulted in only a moderate reduction in scratch depth, particularly for the DLC coating, whose values remained relatively high. The combined quenching and Tenifer treatment again improved scratch resistance compared with the untreated condition, although the reduction was generally lower than that achieved by quenching alone.

Overall, the results demonstrate that substrate treatment exerts a stronger influence on scratch resistance than coating type. Among the investigated treatments, quenching produced the greatest reduction in scratch depth for both steels, highlighting the importance of substrate hardness and load-bearing capacity during tribological contact. The Tenifer treatment alone provided more limited benefits, whereas the combined quenching and Tenifer treatment yielded intermediate behavior. A comparison between both steels indicates that AISI P20+Ni generally exhibited lower scratch depths after treatment than AISI 420 modified steel, suggesting a more favorable interaction between the substrate and the deposited coatings. Furthermore, while the MoS₂+Nb coating consistently reduced penetration depth under most conditions, the DLC coating exhibited a stronger dependence on substrate treatment, achieving its best performance when deposited on quenched substrates. These findings confirm that the optimization of tribological performance requires not only the selection of an appropriate coating but also the careful design of the substrate treatment prior to deposition.

3.3 SEM Analysis of Scratch Tracks on AISI 420 Modified Steel

Figure 6 presents representative scratch tracks obtained on AISI 420 modified steel under different substrate conditions: (a) untreated, (b) quenched, (c) Tenifer-treated, and (d) quenched plus Tenifer-treated. Significant differences in scratch morphology were observed, indicating the strong influence of substrate treatment on the mechanical response of the coating-substrate system.



Representative optical micrographs of scratch tracks produced on AISI 420 MOD steel under different substrate conditions: (a) untreated, (b) quenched, (c) Tenifer-treated, and (d) quenched plus Tenifer-treated.

The untreated condition (Figure 6a) exhibited the widest and most pronounced scratch track. A substantial amount of material displacement was observed along the groove boundaries, indicating severe plastic deformation and limited resistance to localized loading. The broad scratch morphology is consistent with the relatively high average scratch depth measured by profilometry and reflects the lower load-bearing capacity of the untreated substrate.

After quenching (Figure 6b), a remarkable reduction in scratch width and groove visibility was observed. The scratch track became significantly narrower and less pronounced than that of the untreated condition, indicating improved resistance to penetration. This behavior can be attributed to the increased hardness produced by the quenching treatment, which reduced plastic deformation and enhanced the ability of the substrate to support the applied load. The reduced scratch dimensions are in agreement with the lower PROM values obtained from profilometric measurements.

The Tenifer-treated condition (Figure 6c) exhibited an intermediate response. Although the scratch track remained clearly visible, the groove appeared narrower than that of the untreated specimen. However, evidence of material displacement and localized deformation was still observed along the scratch path. These observations suggest that the Tenifer treatment improved surface hardness but was less effective than quenching in reducing scratch-induced deformation.

The combined quenching and Tenifer treatment (Figure 6d) produced the most homogeneous scratch morphology. The groove was narrow and exhibited reduced material accumulation along its edges, indicating improved resistance to plastic deformation and enhanced substrate support. The absence of severe damage features such as extensive cracking or large-scale delamination suggests that the dominant failure mechanism was mild plastic grooving rather than catastrophic coating failure.

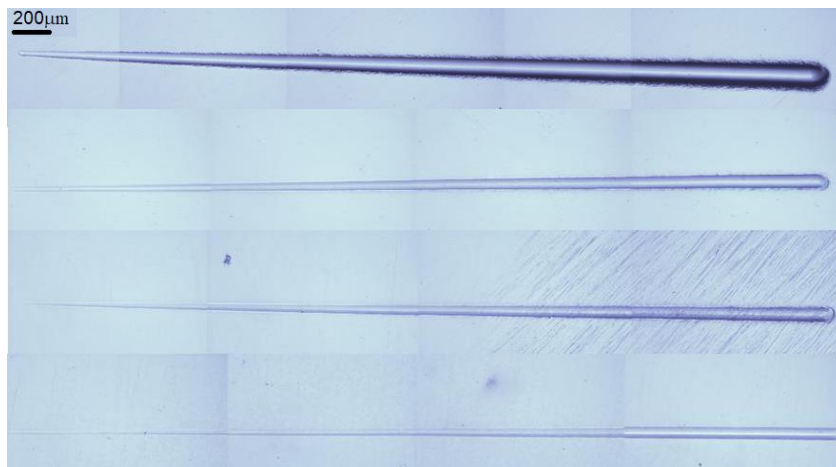
A comparison of the four conditions indicates that substrate hardening plays a critical role in determining scratch resistance. The untreated specimen exhibited the greatest susceptibility to plastic deformation, whereas the quenched and quenched-plus-Tenifer-treated specimens showed significantly improved performance. These observations are consistent with the profilometry results, which revealed lower scratch depths after heat treatment. The SEM analysis therefore confirms that the improvement in scratch resistance is primarily associated with the increased load-bearing capacity provided by substrate hardening rather than changes in coating composition alone.

Overall, the combined use of profilometry and scratch-track observations demonstrates that heat treatment significantly enhances the tribological performance of AISI 420 modified steel by reducing penetration depth, limiting plastic deformation, and improving the mechanical stability of the coating-substrate system.

3.4 SEM Analysis of Scratch Tracks on AISI P20+Ni Steel

Figure 6 presents representative optical micrographs of the scratch tracks produced on AISI P20+Ni steel subjected to different substrate treatments. Significant differences in scratch morphology were observed, demonstrating the strong influence of substrate conditioning on the mechanical response of the coating-substrate system during scratching.

The untreated condition (Figure 6a) exhibited the widest and most pronounced scratch track. Considerable material displacement was observed along the groove boundaries, indicating extensive plastic deformation and limited resistance to penetration. The broad morphology of the scratch track is consistent with the relatively high profilometric depth measured for this condition, confirming the reduced load-bearing capacity of the untreated substrate.



Representative optical micrographs of scratch tracks produced on AISI P20 steel under different substrate conditions: (a) untreated, (b) quenched, (c) Tenifer-treated, and (d) quenched plus Tenifer-treated.

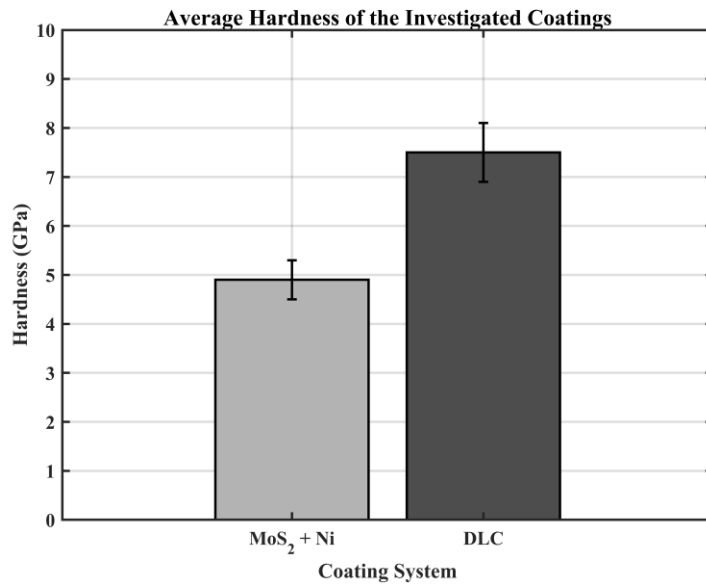
Following quenching (Figure 6b), the scratch track became significantly narrower and less visible. The reduction in groove width and the absence of severe material accumulation indicate an improvement in scratch resistance resulting from the increased substrate hardness. This observation is in agreement with the profilometry results, which revealed a substantial decrease in average scratch depth after heat treatment.

The Tenifer-treated specimen (Figure 6c) exhibited an intermediate behavior. Although the scratch track remained clearly visible, its width was smaller than that observed for the untreated condition. Evidence of localized plastic deformation was still present, suggesting that the thermochemical treatment improved surface properties but did not provide the same level of mechanical support achieved through quenching. This observation is consistent with the profilometric measurements, which showed only a moderate reduction in scratch depth.

The combined quenching and Tenifer treatment (Figure 6d) produced the most favorable scratch morphology. The groove was narrow, uniform, and characterized by minimal material accumulation along its edges. No evidence of severe cracking, delamination, or catastrophic coating failure was observed. The homogeneous appearance of the scratch track indicates improved load distribution and enhanced support of the coating by the hardened substrate. These observations correlate well with the lowest scratch depths measured during profilometric analysis.

A comparison of the four conditions demonstrates that substrate hardening is the primary factor governing scratch resistance in AISI P20+Ni steel. While the Tenifer treatment alone provided a moderate improvement, quenching significantly reduced plastic deformation and scratch penetration. The combined treatment further enhanced the uniformity of the scratch track and minimized damage accumulation. These results are consistent with the friction and profilometry analyses and confirm that improvements in substrate mechanical properties directly contribute to enhanced tribological performance.

3.5 Correlation Between Hardness and Tribological Performance



Average NanoHardness of the Investigated Coatings

The nanoindentation figure 7 results provide a clear explanation for the tribological behavior observed during the friction and scratch tests. The DLC coating exhibited an average hardness approximately 50% higher than that of the MoS_2+Nb coating, indicating a superior resistance to plastic deformation under localized loading conditions. This increased hardness is consistent with the lower scratch depths measured for several DLC-coated specimens, particularly after substrate hardening treatments, where the enhanced load-bearing capacity of the coating-substrate system reduced indenter penetration and material displacement. In contrast, although the MoS_2+Nb coating exhibited lower hardness values, it consistently produced the lowest coefficients of friction, demonstrating that its tribological performance is primarily governed by its solid-lubrication mechanism rather than its mechanical strength. Consequently, the results reveal two distinct performance trends: the DLC coating provides superior resistance to scratch-induced damage due to its higher hardness, whereas the MoS_2+Nb coating is more effective in minimizing friction during sliding contact. The combined analysis of hardness, coefficient of friction, and scratch depth therefore indicates that the optimal coating selection depends on the dominant service requirement. For applications where wear resistance and mechanical durability are critical, DLC coatings deposited on hardened substrates represent the most suitable solution. Conversely, for applications requiring low friction and reduced energy dissipation, the MoS_2+Nb coating offers significant advantages. These findings highlight the importance of simultaneously considering mechanical and tribological properties when designing advanced surface engineering systems for tooling applications.

3.6 Correlation Between Friction, Scratch Resistance and Hardness

The combined analysis of the friction, scratch, and nanoindentation results provides a comprehensive understanding of the tribological behavior of the investigated coating systems. Although both coatings improved the surface performance of AISI P20+Ni and AISI 420 modified steels, significant differences were observed in the mechanisms governing friction reduction and resistance to mechanical damage.

The friction measurements demonstrated that the MoS_2 +Nb coating consistently exhibited the lowest coefficient of friction under all substrate conditions. The lowest COF values were obtained after the combined quenching and Tenifer treatment, reaching approximately 0.071 and 0.085 for AISI P20+Ni and AISI 420 modified steel, respectively. These results confirm the effectiveness of the solid-lubrication mechanism provided by the MoS_2 phase, which reduces interfacial shear stresses during sliding contact. In contrast, the DLC coating generally exhibited higher friction coefficients, despite its superior mechanical properties.

The profilometric analysis revealed a different trend. The reduction in scratch depth was strongly influenced by substrate hardening, particularly after quenching treatment. For both steels, the lowest penetration depths were generally associated with the hardened substrates, indicating that scratch resistance depends primarily on the load-bearing capacity of the coating-substrate system. The optical analysis of the scratch tracks further confirmed these observations, showing narrower grooves and reduced plastic deformation after quenching and combined quenching-Tenifer treatments.

Nanoindentation measurements provided a mechanistic explanation for the observed scratch behavior. The DLC coating exhibited an average hardness approximately 50% higher than that of the MoS_2 +Nb coating, indicating a significantly greater resistance to localized plastic deformation. This higher hardness explains the improved resistance to scratch penetration observed for the DLC-coated specimens, particularly when deposited on hardened substrates. Conversely, the lower hardness of the MoS_2 +Nb coating contributed to larger deformation during scratching despite its superior friction-reducing capability.

A comparison between the two substrate materials indicates that both steels responded similarly to the applied treatments. However, AISI P20+Ni generally exhibited lower scratch depths and more uniform scratch morphologies after treatment, suggesting a more favorable interaction between the substrate and the deposited coatings. The beneficial effect of quenching was evident in both materials, whereas the Tenifer treatment alone produced a more moderate improvement in tribological performance.

The results demonstrate that friction reduction and scratch resistance are controlled by different mechanisms and should therefore be evaluated independently. While the MoS_2 +Nb coating provides excellent friction reduction through solid lubrication, the DLC coating offers superior protection against mechanical damage owing to its higher hardness and resistance to plastic deformation. Consequently, the optimal coating selection

depends on the specific service requirements. Applications where low friction is the primary objective may benefit from MoS_2 +Nb coatings, whereas applications requiring high wear resistance and enhanced mechanical durability are more likely to benefit from DLC coatings deposited on hardened substrates.

Overall, the present study demonstrates that the combination of substrate hardening and advanced surface engineering treatments is essential for maximizing tribological performance. Among the investigated conditions, quenched substrates coated with DLC exhibited the highest resistance to scratch-induced damage, whereas MoS_2 +Nb coatings provided the lowest friction coefficients. These findings highlight the importance of simultaneously considering friction, hardness, and scratch resistance when designing coating systems for tooling and tribological applications.

4 Conclusions

Based on the tribological, profilometric, scratch, and nanoindentation analyses performed on MoS_2 +Nb and DLC coatings deposited on AISI P20+Ni and AISI 420 modified steels subjected to different substrate treatments, the following conclusions can be drawn:

1. The substrate treatment significantly influenced the tribological performance of both steels. Quenching produced the greatest improvement in scratch resistance, reducing the average scratch depth by approximately 65% in AISI P20+Ni and 70% in AISI 420 modified steel compared with the untreated condition. The combined quenching and Tenifer treatment also improved scratch resistance, although its effect was less pronounced than that of quenching alone.
2. The MoS_2 +Nb coating consistently exhibited the lowest coefficients of friction under all substrate conditions. The minimum COF values were obtained after the combined quenching and Tenifer treatment, reaching approximately 0.071 for AISI P20+Ni and 0.085 for AISI 420 modified steel. These results confirm the effectiveness of the solid-lubrication mechanism provided by the MoS_2 phase in reducing friction during sliding contact.
3. Nanoindentation measurements revealed that the DLC coating exhibited an average hardness approximately 50% higher than that of the MoS_2 +Nb coating. This higher hardness resulted in superior resistance to scratch-induced damage and lower penetration depths, particularly when combined with substrate hardening treatments. Consequently, while MoS_2 +Nb coatings are more effective for friction reduction, DLC coatings provide enhanced mechanical protection and scratch resistance, making them more suitable for applications requiring high wear resistance and load-bearing capability.

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