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Protective effectiveness of a nanocomposite coating with low-friction layers under sliding friction at ambient temperature

Marek Robert Hawryluk[1,2*], Tadeusz Leśniewski[1], Marek Wiergowski[3]

[1] Wroclaw University of Science and Technology, Wybrzeże Stanisława Wyspiańskiego 27, 50-370 Wrocław, Poland
[2] Center for Materials Science and Metal Forming, Lukasiewicza 5, 50-371 Wroclaw, Poland
[3] GKN Driveline Polska Sp. z o.o., 56-400 Olesnica, Poland
* Corresponding author's e-mail: marek.hawryluk@pwr.edu.pl

ABSTRACT

This study evaluates the protective effectiveness of a PVD nanocomposite coating (Alwin XC), consisting of a nanocrystalline chromium aluminum silicon nitride (CrAlSiN) base layer combined with a TiC/C low-friction layer) deposited on Orvar 2M hot-work tool steel under sliding friction conditions at ambient temperature. Tribological tests were carried out using the ball-on-disc method under technically dry friction, with a silicon nitride (Si_3N_4) ceramic ball serving as the counterbody. The tribological behavior of the coated system was directly compared with that of uncoated Orvar 2M steel, with particular emphasis on the quantitative analysis of wear-track geometry. The obtained results were additionally referenced against preliminary tribological data acquired at elevated temperatures, suggesting the possible contribution of tribo-oxidative processes to coating performance. The results demonstrate a pronounced improvement in wear resistance resulting from the application of the Alwin XC coating. For uncoated Orvar 2M steel, the maximum wear-track depth ranged from 14 to 20 µm, with wear areas of approximately 8000–12,000 µm². In contrast, for the Orvar 2M + Alwin XC system, the wear-track depth did not exceed 2–7 µm, while the wear area was limited to 1400–3000 µm². These differences indicate a significant reduction in wear intensity and a fundamental modification of the sliding contact conditions in the presence of the coating. Microscopic analyses confirmed that uncoated steel undergoes intensive abrasive wear accompanied by plastic deformation of the near-surface layer, whereas the Alwin XC coating stabilizes the tribological contact, leading to the formation of shallow and narrow wear tracks. The scientific novelty of this work lies in quantitatively demonstrating that the Alwin XC coating not only reduces wear but also substantially alters the contact geometry by limiting the real contact area, acting as an effective load-bearing layer under ambient-temperature conditions, and suggesting potential tribo-oxidative mechanisms at elevated temperatures.

Keywords: tribological tests, Orvar 2m, PVD coating (Alwin XC), abrasive wear, sliding friction.

INTRODUCTION

Physical vapor deposition (PVD) coatings are widely applied to enhance the wear resistance of components operating under sliding friction conditions. In the literature, particular attention is given to coatings intended for elevated-temperature applications, especially in the context of hot forming tools, where the dominant degradation mechanisms include adhesive–abrasive wear, oxidation, and thermal effects [1–3]. As a result, a substantial body of research focuses on the tribological behavior of PVD coatings under high-temperature conditions and high contact loads.

In contrast, the quantitative analysis of wear-track geometry at ambient temperature is addressed far less frequently, despite its role as a crucial reference point for interpreting degradation processes occurring under more severe conditions. Tests conducted at room temperature enable the separation of intrinsic coating properties from thermally activated phenomena such as diffusion, phase transformations, or intensive oxidation [4,5]. The absence of such a reference complicates the unambiguous assessment of changes in wear mechanisms observed at elevated temperatures. In particular, the literature lacks systematic quantitative studies aimed at determining the extent to which PVD coatings modify the actual contact area and wear-track geometry compared to uncoated tool steels. Parameters such as maximum wear-track depth or wear area provide essential information regarding contact load-bearing capacity and the effectiveness of the coating as a load-transferring layer [6–8].

Hot-work tool steels constitute a key class of structural materials in industrial applications such as metal forming, extrusion, and forging [9,10], where tool working surfaces are exposed to extreme frictional conditions, high temperatures, and cyclically varying thermo-mechanical loads. These conditions lead to thermal cracking, fatigue, and adhesive or abrasive wear [11–14,15]. Previous studies have shown that the wear mechanisms of these materials involve galling and adhesive material transfer, as well as plastic deformation and surface layer degradation during sliding contact, which is particularly evident in ball-on-disc tribological tests and microscopic analyses [16–18].

PVD coatings and modified surface systems, such as nitriding or duplex treatments, have been extensively investigated to improve wear resistance at elevated temperatures. For example, multilayer coatings exhibit reduced adhesion and limited material transfer under extreme thermal conditions [11,12], while nanocomposite PVD coatings enhance resistance to abrasive wear and improve the microstructural stability of tools [13]. Furthermore, studies on the behavior of tool steels under cyclic thermal and mechanical loading indicate that the combination of coatings and surface modifications plays a critical role in extending tool lifetime [14,17]. Investigations into the mechanical and tribological properties of tool steels have also demonstrated that additional coatings, such as W-DLC with a Cr interlayer, can improve wear resistance and reduce surface deformation [15]. At the same time, in processes such as hot stamping, tool temperature and steel composition significantly influence friction and wear behavior [18–20]. The literature emphasizes that the effectiveness of coatings and surface modifications depends on their ability to reduce adhesion, limit material transfer, and maintain stability under combined thermal and mechanical loading, making this issue a key aspect in the design of forging tools with extended service life [21–22]. Overall, the reviewed studies clearly indicate that further systematic investigations in this field are well justified. The continued development of measurement techniques and analytical approaches for identifying wear phenomena and degradation mechanisms, both under laboratory conditions and in industrial processes, is essential for advancing the understanding of tribological behavior at elevated temperatures. Such studies support the refinement of experimental methodologies and contribute to the further development of tribology as a scientific discipline [23–24].

The aim of the present study is to provide a quantitative assessment of the protective effectiveness of the PVD Alwin XC coating deposited on Orvar 2M steel under sliding friction conditions at ambient temperature, serving as a reference for subsequent analyses conducted at elevated temperatures.

MATERIALS AND METHODS

Substrate material and coating

This study evaluates the protective effectiveness of the ALWIN XC coating deposited directly on Orvar 2M hot-work tool steel. No additional surface pretreatment or diffusion nitriding was applied prior to coating deposition. The investigated material system and the coating were characterized in terms of chemical composition and mechanical properties, including Young's modulus and hardness, as well as their tribological behavior under sliding friction conditions at ambient temperature.

The Orvar 2M tool steel exhibits of tempered martensite with fine carbide precipitates uniformly distributed within the post-martensitic ferritic matrix. It provides the high wear resistance and mechanical strength of the steel. The ALWIN XC coating is characterized by a dense and uniform nanocrystalline CrAlSiN structure with the CrN interlayer and embedded TiC particles. It`s Young's modulus of the coating ($E \approx 500$–560 GPa), while hardness is 26–28 GPa.

The key properties of the investigated materials are summarized in Table 1, where Orvar 2m steel and this steel coated with ALWIN XC are compared in terms of chemical composition, hardness, Young's modulus, and selected mechanical and elastic parameters. The table highlights the significant differences between the substrate steel and the ALWIN XC coating.

Table 1. Comparison of chemical composition and mechanical properties of Orvar 2M and AlWiN XC

Parameter	Orvar 2m (steel)	ALWIN XC (coating)
Chemical composition / coating system	Cr-Mo-V-Si tool steel (EN X40CrMoV5-1, AISI H13): C ~0.35–0.42%, Si ~0.8–1.2%, Mn ~0.25–0.50%, Cr ~4.8–5.5%, Mo ~1.2–1.5%, V ~0.85–1.15%	Nanocrystalline CrAlSiN coating with TiC; TiC reduces the friction coefficient and limits material adhesion
Hardness	44–52 HRC after quenching and tempering	26–28 GPa (aprox. 2650–2850 HV)
Young Modulus (E)	~210–215 GPa	500–560 GPa
Heat treatment / condition	Quenching + tempering; resistance to thermal cracking	Applied directly onto the steel surface; without nitriding
Deposition method / technology	Traditionally	Hybrid PVD: magnetron sputtering + low-voltage arc deposition
Coating thickness	–	7–8.5 µm
Thermal stability / operating temperature	Up to ~600 °C, typical for heat-treated tool steel	Up to ~1100 °C; high resistance to oxidation and material adhesion

While Orvar 2m provides the bulk mechanical properties and thermal resistance, the nanocrystalline coating substantially enhances surface hardness, elastic modulus, thermal stability, and reduces friction and adhesion, demonstrating the complementary roles of the steel–coating system.

Tribological tests

The tribological tests were performed using a DUCOM ball-on-disc tribometer under technically dry sliding conditions. The specimens were discs of uncoated Orvar 2M steel and discs coated with the patented PVD Alwin XC coating (SHM, Czech Republic). A Si_3N_4 ceramic ball was used as the counterbody. All tests at ambient temperature were conducted under a constant normal load of 20 N, a sliding speed of 0.1 m/s, and a test duration of 5000 s, with a wear track radius of 6 mm. These parameters were chosen to represent typical operating conditions of hot-work tooling in forging processes, ensuring that the results are relevant for practical applications. During each test, the friction force was continuously recorded, allowing determination of the coefficient of friction. The main test parameters are summarized in Table 2.

High-temperature tests were performed by inductively heating the disc to simulate conditions approaching those in hot forging applications. These tests aimed to provide preliminary insights into the thermal stability and wear resistance of the Alwin XC coating under elevated temperatures. A detailed characterization of high-temperature behavior is beyond the scope of the present study and will be addressed in future work. The design of the experimental setup and selection of parameters ensured reproducibility and reliability of the data, allowing direct comparison between uncoated Orvar 2M steel and the coated system.

Wear assessment methods and analysis of wear track geometry

The wear intensity was evaluated based on the volumetric wear Zobj and the wear factor Wx, which takes into account the applied normal load and the sliding distance. The wear factor was calculated according to the relationships (1–2):

$$W_z = \frac{Z_{obj}}{F \cdot s}\left[\frac{m^3}{N \cdot m}\right] \tag{1}$$

where: W_z – wear index, $Z_{obj.}$ – volumetric wear determined for the entire abrasive wear track, F – load, S – sliding distance.

$$Z_{obj.} = P_{Aśr} \cdot Obw \ [\mathrm{m}^3] \tag{2}$$

Table 2. Average maximum wear depth and track area for Orvar 2m and Orvar 2M + Alwin XC systems at ambient and elevated temperatures. Min.–Max. indicates the range of values obtained from four repetitions of the test

Material / Temperature	Max. depth (µm) (mean ± min–max)	Track area (µm²) (mean ± min–max)	Z_{obj} (m³)	Wz, [m³/(N·m)]
Orvar 2M – 21 °C	18.18 ± 4.5	8650 ± 820	3.63×10^{-10}	3.63×10^{-14}
Orvar 2M + Alwin XC – 21 °C	3.75 ± 2.5	1640 ± 230	6.18×10^{-11}	6.18×10^{-15}
Orvar 2M + Alwin XC – 200 °C	6.38 ± 2.8	2522 ± 1137	9.51×10^{-11}	9.51×10^{-15}
Orvar 2M + Alwin XC – 400 °C	14.55 ± 4.6	1723 ± 1152	1.06×10^{-10}	3.53×10^{-14}
Orvar 2M + Alwin XC – 600 °C	18.28 ± 5.7	4430 ± 475	1.67×10^{-10}	5.57×10^{-14}

where: Z_{obj}. – determined for the entire abrasive wear track, $P_{Aśr}$ – average value of the cross-sectional areas of the track measured in three regions, Obw – circumference of the abrasive wear track.

The geometry of the wear tracks was analyzed by scanning the disc wear trace in three selected areas, evenly spaced at 120° intervals (Figure 1), allowing assessment of the repeatability of the wear process. The surface topography of the wear tracks was recorded using a Leica DCM8 interferometric microscope equipped with a 10× objective.

Analysis of the wear tracks, including 2D profiles and 3D topography maps, was performed using MountainsMap Universal software. This procedure enabled determination of the maximum wear depth, track area, and wear volume, which served as the basis for further analysis of the results.

Additionally, a chemical composition analysis of the wear tracks was performed using SEM/EDS, enabling qualitative identification of elements in the tribological contact area.

RESULTS

Wear track geometry at ambient temperature

To quantitatively assess the protective performance of the AlWiN XC coating under ambient temperature conditions, a systematic analysis of the wear track geometry generated during ball-on-disc tribological tests was conducted. The evaluation focused on characteristic geometric features of the tracks, providing a basis for comparing the tribological response of uncoated steel with that of surface-modified variants. From this analysis, key quantitative parameters describing wear depth, track area, and the volume of material removed due to friction were determined.

Analysis of the 2D wear profiles at ambient temperature (Figure 2) reveals clear differences in the tribological contact geometry between uncoated Orvar 2M steel and the Orvar 2M + AlWiN XC system.

For uncoated Orvar 2M steel, the wear profile is characterized by considerable depth and sharply defined track edges, indicating strong counterbody penetration and pronounced

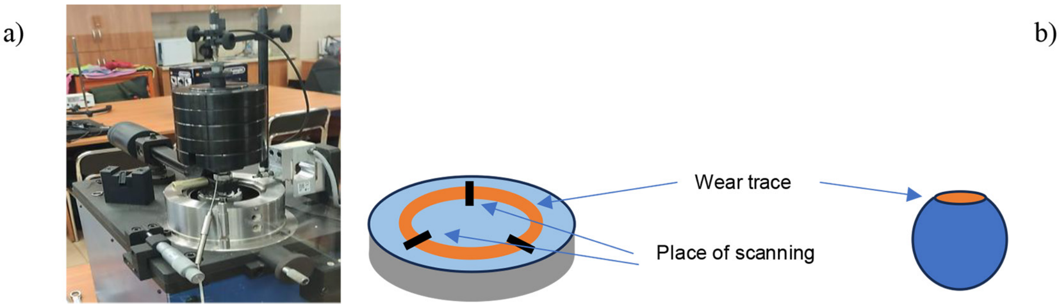


Figure 1. View of: (a) tribotester with devices, (b) schematic of wear tracks on the disc and ball indicating the analyzed locations

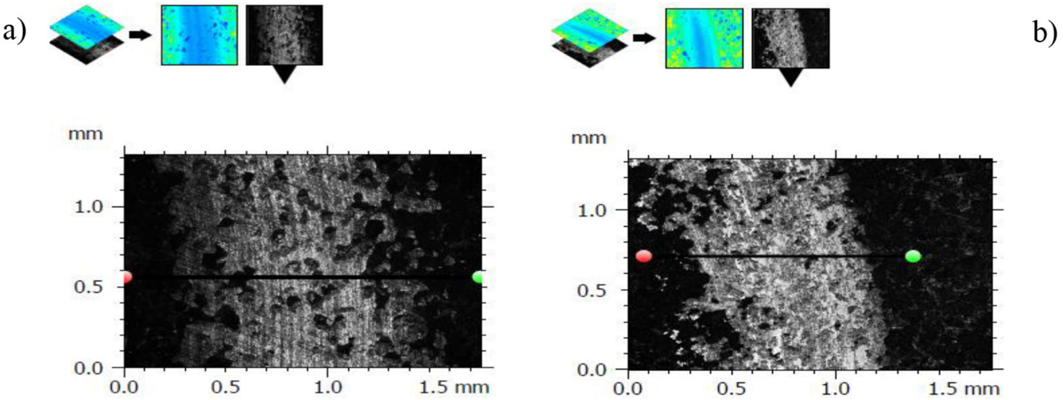
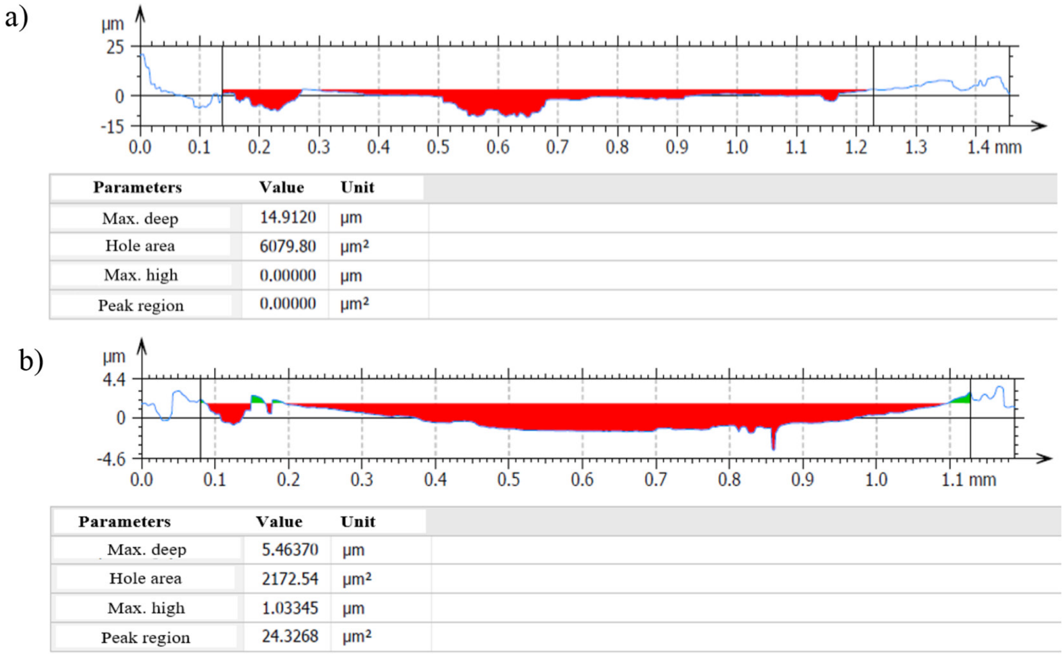


Figure 2. Comparison of 2D wear profiles at ambient temperature for: (a) Orvar 2M steel, (b) Orvar 2M + AlWiN XC system

development of abrasive grooves. In contrast, the AlWiN XC-coated samples exhibit significantly shallower and more regular profiles, with a smooth wear-track base, reflecting a more stable contact behavior and a reduction in the actual contact area. These differences confirm that the presence of the coating fundamentally alters the wear track geometry, promoting a more uniform distribution of loads under ambient friction conditions. To quantitatively evaluate the protective performance of the AlWiN XC coating, measurements of maximum wear track depth and track area were performed at different operating temperatures of the tribological system. The disc wear tracks were scanned in three selected areas spaced approximately 120° apart (Figure 1). Representative 2D wear profiles at ambient temperature (Figure 3) further highlight notable differences in the tribological contact geometry between uncoated Orvar 2M steel and the Orvar 2M + AlWiN XC system. For Orvar 2M, the maximum wear depth reaches approximately 14.9 µm, while the corresponding cross-sectional area of the track is relatively small at around 6080 µm², indicating deep counterbody penetration and locally intensive wear. For the AlWiN XC-coated sample, the maximum profile depth is considerably lower, approximately 5.5 µm, while the cross-sectional area of the track increases to around 2173 µm², indicating a flatter and more distributed wear track. The change in the ratio between depth and track area suggests that the AlWiN XC coating reduces the concentration of contact stresses and promotes a stable, load-bearing contact behavior under ambient friction conditions. Detailed results for the Orvar 2M + ALWIN XC system at 200 °C, 400 °C, and 600 °C are not presented in this study [25], as they will be addressed in separate, dedicated investigations. For the purposes of comparison, only selected quantitative parameters are shown here, providing a reference point for the detailed data obtained for Orvar 2M and Orvar 2M with ALWIN XC at ambient temperature. The average values of maximum wear depth and track area for all material/temperature combinations, along with volumetric wear Z_{obj} and wear factor W_z are presented in Table 3.

The data clearly demonstrate that the AlWiN XC coating significantly reduces wear intensity at ambient temperature – the average maximum depth decreases from 18.18 µm for uncoated Orvar 2M steel to 2.75 µm for the Orvar 2M + AlWiN XC system, while the track area decreases from 9650 µm² to 1640 µm². Increasing the temperature leads to a gradual rise in both maximum depth and track area, indicating the activation of additional surface degradation mechanisms, such as intensified tribochemical and adhesive processes. However, increasing temperature does not lead



Parameters	Value	Unit
Max. deep	14.9120	µm
Hole area	6079.80	µm²
Max. high	0.00000	µm
Peak region	0.00000	µm²

Parameters	Value	Unit
Max. deep	5.46370	µm
Hole area	2172.54	µm²
Max. high	1.03345	µm
Peak region	24.3268	µm²

Figure 3. Representative 2D wear profiles at ambient temperature for uncoated Orvar 2M steel and the Orvar 2M + AlWiN XC system

Table 3. Average maximum wear depth and track area for Orvar 2m and Orvar 2M + Alwin XC systems at ambient and elevated temperatures. Min.–Max. indicates the range of values obtained from four repetitions of the test

Material / Temp	Max. depth [µm] (mean ± min–max)	Track area [µm^2] (mean ± min–max)	Zobj [m^3]	Wz [m^3/(N·m)]
Orvar 2M – 21 °C	18.18 ± 4.5	8650 ± 820	3.63×10^{-10}	3.63×10^{-14}
Orvar 2M + Alwin XC – 21 °C	3.75 ± 2.5	1640 ± 230	6.18×10^{-11}	6.18×10^{-15}
Orvar 2M + Alwin XC – 200 °C	6.38 ± 2.8	2478 ± 221	9.34×10^{-11}	3.11×10^{-14}
Orvar 2M + Alwin XC – 400 °C	14.55 ± 4.6	7112 ± 590	4.13×10^{-10}	1.38×10^{-13}
Orvar 2M + Alwin XC – 600 °C	18.28 ± 5.7	8989 ± 530	3.39×10^{-10}	1.13×10^{-13}

to a monotonic increase in wear depth and track area; instead, a non-linear response is observed, characterized by a reduction in wear parameters at intermediate temperature followed by a pronounced increase at the highest tested temperature. The trends in maximum wear depth and track area as a function of temperature are shown in Figure 4. A clear protective effect of the AlWiN XC coating is evident at ambient temperature, with a gradual loss of effectiveness as the test temperature increases. The vertical whiskers indicate the min.–max. range from repeated measurements, highlighting the repeatability and stability of the results. In contrast to geometrical wear parameters, the volumetric wear Z_{obj} exhibits a monotonic increase with temperature, indicating progressive material loss despite the non-linear evolution of wear track geometry. The results presented in Figure 4 show that the AlWiN XC coating significantly reduces both the maximum wear depth and the wear track area at ambient temperature, indicating effective load-bearing behavior and stable sliding contact. The shallow wear tracks formed under these conditions suggest a mild wear mechanism dominated by abrasive micro-cutting with limited plastic deformation. With increasing temperature, a gradual increase in wear depth and wear track area is observed for the coated system, reflecting progressive degradation of the coating's protective function. At intermediate temperatures

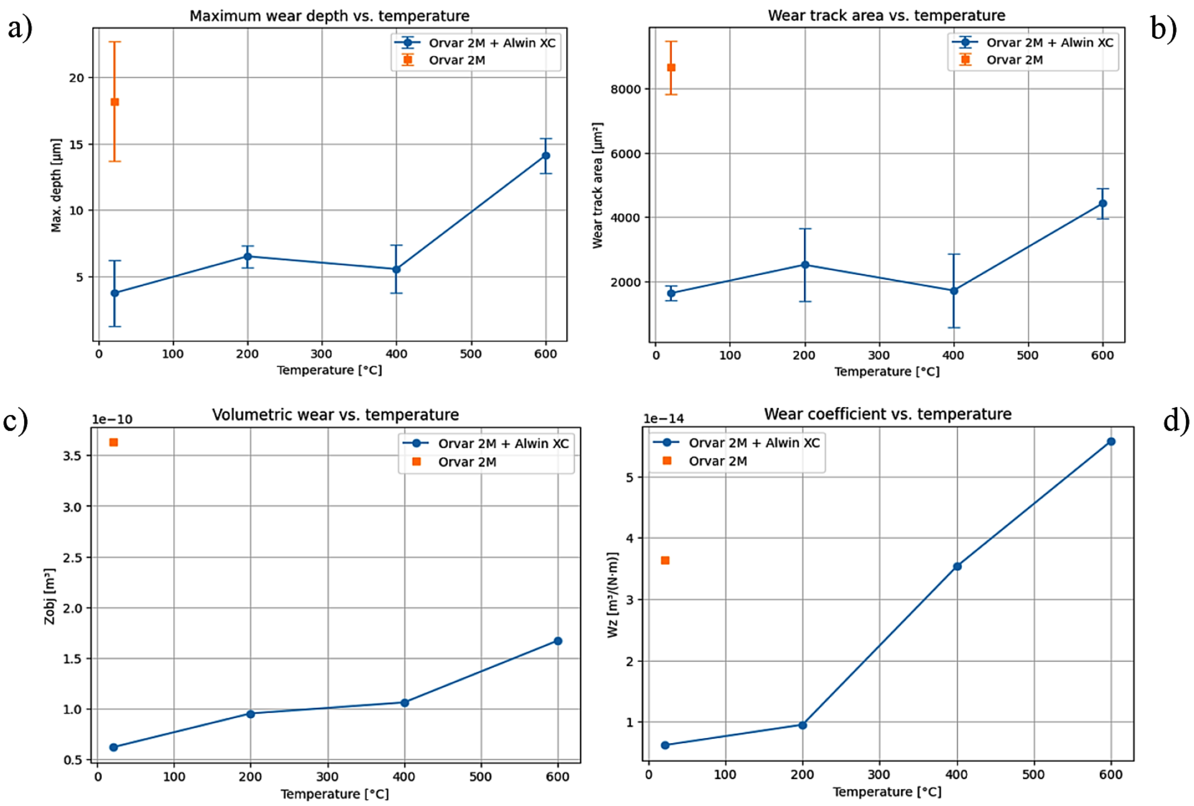


Figure 4. Effect of test temperature on wear track geometry for Orvar 2 m and Orvar 2M + Alwin XC systems: a) maximum wear depth (µm), b) wear track area (µm²)

(200–400 °C), this trend is associated with thermally activated tribochemical reactions and the onset of adhesive interactions, while at 600 °C a transition toward a mixed abrasive–adhesive wear regime occurs due to partial coating breakdown and increased substrate involvement. It should be noted that the sliding distance differed between test conditions: 500 m was used at 200°C, whereas 150 m was applied at 400 °C and 600 °C, which may slightly complicate direct comparison of wear magnitudes between temperatures

In contrast, uncoated Orvar 2M steel exhibits severe wear already at ambient temperature, characterized by deep and wide wear tracks resulting from intensive abrasive wear and plastic deformation. Despite temperature-induced degradation, the AlWiN XC coating maintains superior wear resistance over the investigated temperature range by delaying the activation of severe wear mechanisms and reducing the real contact area. Mechanistic perspective: The high hardness and elastic modulus of the ALWIN XC coating reduce the real contact area, limiting plastic deformation and explaining shallower wear tracks compared to uncoated steel. TiC particles in the coating further stabilize the contact and reduce friction. Although detailed numerical modeling was not performed, the observed trends are consistent with contact mechanics principles and provide a mechanistic rationale for the quantitative differences between coated and uncoated samples.

Repeatability and stability of wear

To establish the structural basis for the observed wear behavior, the initial microstructure of the investigated material systems was examined. Figure 5 presents microstructural images of the Orvar 2M tool steel substrate and the substrate–coating system with the ALWIN XC coating.

The microstructure of Orvar 2M tool steel (Figure 5a) consists predominantly of tempered martensite with uniformly distributed fine carbide precipitates, providing the bulk mechanical properties and thermal resistance. The ALWIN XC coating (Figure 5b) is composed of a dense nanocrystalline CrAlSiN layer with a CrN interlayer (~1.5 µm) and embedded TiC particles, with a total thickness of 7–8.5 µm. The coating exhibits a high Young's modulus (E ≈ 500–560 GPa) and hardness (26–28 GPa), enhancing surface mechanical properties and thermal stability.

These microstructural observations provide the structural context for interpreting the wear features observed after testing. The following analysis therefore examines the repeatability and geometry of the resulting wear tracks. Analysis of three wear track regions, spaced at 120° intervals, revealed high repeatability of the results across all test repetitions, for both uncoated Orvar 2M steel and the Orvar 2M + AlWiN XC system. The 3D topography scans presented in Figure 6 correspond to representative sections of the wear tracks, selected based on the agreement of maximum depth and track area values with the average values obtained for the entire wear path.

The presented 3D images can therefore be regarded as a reliable illustration of the characteristic wear geometry for the examined material systems at ambient temperature. For uncoated Orvar 2M steel, an irregular wear track geometry is observed, with local depressions of approximately 14–20 µm and a pronounced non-uniformity in height distribution across the track. The color-coded height maps indicate regions of intensive plastic deformation and localized wear, confirming an unstable sliding contact and the dominance of abrasive–adhesive wear mechanisms.

In contrast, the 3D topography of Alwin XC -coated Orvar 2m samples reveals a fundamentally

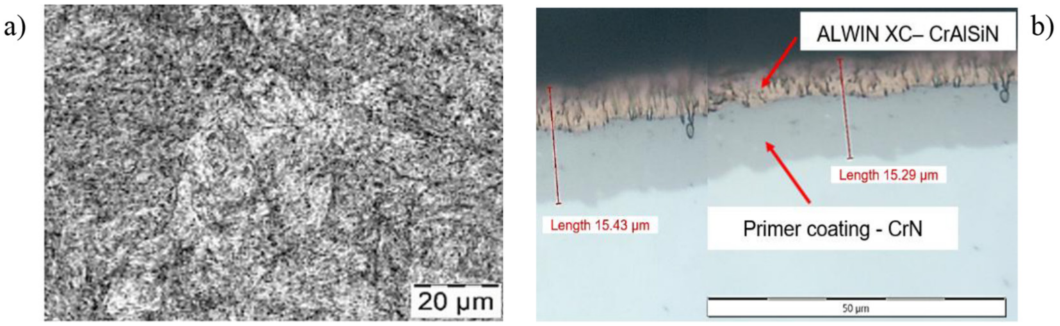


Figure 5. Microstructure of the investigated material: a) quenched and tempered Orvar 2m tool steel; b) Orvar 2m steel with the PVD ALWIN XC coating

different wear pattern. The maximum wear depth does not exceed 2–7 µm, and the height distribution is much more uniform across the track width. The absence of deep local depressions and the gentle height gradient indicate a stable friction process and limited subsurface material deformation. Additionally, the wear track area is significantly smaller (approximately 1400–3000 µm²) compared to uncoated steel, for which it reaches 8000–12000 µm².

These 3D scans play a key role in visually confirming the quantitative results presented in the tables and clearly demonstrate that the AlWiN XC coating not only reduces wear intensity but also modifies the tribological contact geometry by limiting the real contact area and stabilizing friction conditions at ambient temperature. This effect supports the protective and load-bearing function of the coating, in agreement with the conclusions outlined in the abstract. It should be noted that these observations are based on representative 3D scans (Figure 6) rather than a full statistical analysis. The consistency of features observed across multiple scanned areas suggests that the reported trends are reproducible within the scope of the tested samples.

Microscopic analysis of cross-sections after the tribological tests (Figure 6) reveals marked differences in wear mechanisms depending on the presence of the AlWiN XC coating. For uncoated Orvar 2M steel, the wear track exhibits irregular geometry, localized plastic deformation, and uneven surface distribution, indicating unstable sliding contact dominated by abrasive–adhesive mechanisms, with subsurface material undergoing localized plastic flow. For AlWiN XC-coated Orvar 2M samples, the wear pattern is fundamentally different. The track is more uniform, and subsurface deformation is limited. The absence of strongly localized deformations and the even track profile indicate a stable friction process with predominance of milder abrasive mechanisms, while material degradation in the subsurface zone is minimized. These visual observations are consistent across several representative sections, highlighting the qualitative stability imparted by the AlWiN XC coating. In uncoated Orvar 2M, wear was dominated by abrasive processes combined with localized subsurface plastic deformation, resulting in irregular strain distribution and stress concentration in contact areas

Microscopic observations indicate local fluctuations in wear intensity, characteristic of unstable sliding contact. Overall, these results provide a representative qualitative assessment of wear behavior and stability in the tested samples. The observed uniformity of wear tracks in coated samples and the consistent differences compared to uncoated samples support the visual reproducibility of the results. While these observations are qualitative, they offer clear insights into the protective role of the AlWiN XC coating and

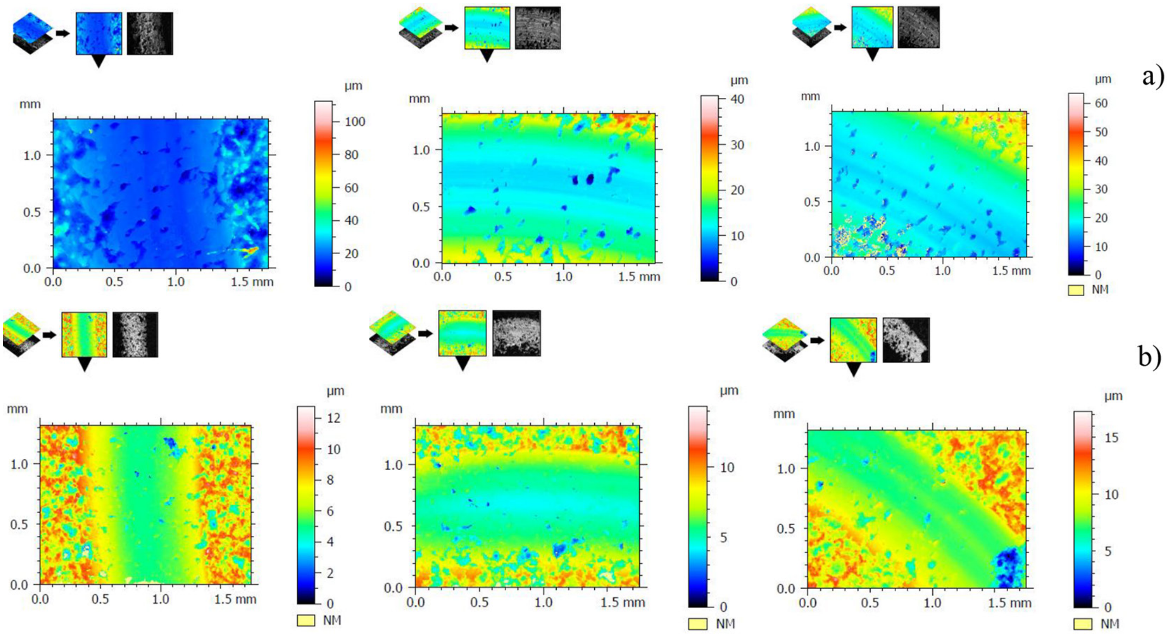


Figure 6. 3D scans of representative wear track sections corresponding to average maximum depth and track area values: a) Orvar 2M (uncoated), b) Orvar 2M + Alwin XC

the associated stabilization of friction conditions under the tested conditions (Figure 7).

The application of the Alwin XC coating leads to a pronounced modification of the wear mechanism. The wear tracks are narrower and more uniform, while subsurface deformation is significantly reduced. Stabilization of the contact decreases the intensity of micro-cutting and plastic deformation, thereby reducing the real contact area and local contact stresses. Observations of the 3D surface topography confirm a mild wear regime, in which the dominance of abrasive mechanisms gives way to a stable and controlled surface interaction. In summary, the Alwin XC coating enhances the tribological stability of the contact, limits plastic deformation and stress concentrations, and ensures a predictable and gentle friction process.

For a more comprehensive assessment, the variation of the coefficient of friction as a function of sliding distance over the entire measured path of 100 m was also determined. The results are presented in Figure 8.

Analysis of the friction curves indicates that no significant differences in the coefficient of friction were observed between the two investigated

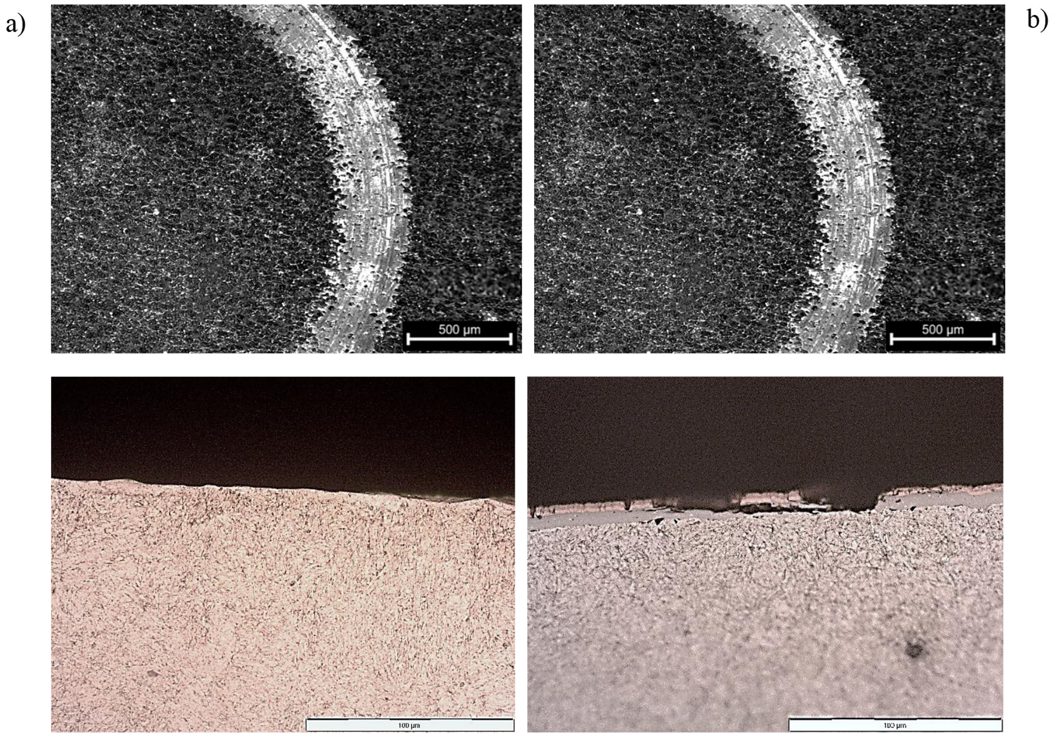


Figure 7. Views of wear profiles (top) after testing and cross-sections (bottom) of Orvar 2M steel after tribological tests: (a) Orvar 2M steel, (b) Orvar 2M steel with Alwin XC coating; LM images, etched condition

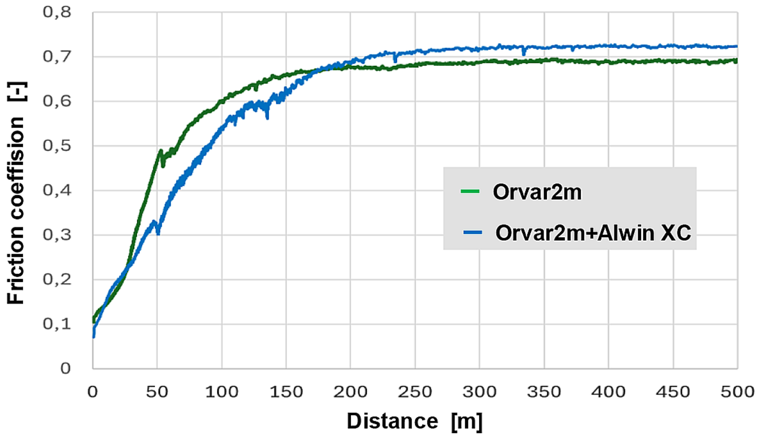


Figure 8. Variation of the coefficient of friction as a function of sliding distance; upper plot – Orvar 2m steel, lower plot – Orvar 2m steel with Alwin XC coating

material variants, with values stabilizing around 0.7. Initially, the Alwin XC coating exhibits a lower friction coefficient compared to uncoated Orvar 2M steel, suggesting the formation of a protective, low-shear tribological film that reduces interfacial resistance. However, as sliding progresses and the coating layer experiences localized breakdown, the friction coefficient gradually increases, eventually exceeding that of the bare steel. This behavior can be attributed to the exposure of the substrate and possible adhesive interactions at the contact interface once the coating is compromised. The results highlight the dynamic nature of the coating's protective mechanism and underline the importance of coating integrity for sustained friction reduction.

Directions for future research

The presented results are complemented by preliminary tribological tests performed at elevated temperatures of 200, 400, and 600 °C, which form the basis for further investigation of the Alwin XC coating under conditions relevant to hot forging. Future research will focus on validating the laboratory findings under real industrial conditions, where tools are subjected to cyclic thermomechanical loads, high contact pressures, and rapid temperature variations. The specific scientific gap addressed by the planned studies lies in understanding the high-temperature tribological behavior of AlWiN XC coatings on Orvar 2M steel without prior diffusion nitriding, which has not been systematically investigated. A key novelty of the planned work is the systematic evaluation of hybrid surface engineering concepts using a CrN interlayer as an unconventional alternative to standard industrial solutions, with a focus on linking coating design to measurable improvements in high-temperature wear performance.

CONCLUSIONS

This work investigates the tribological performance and protective effectiveness of a nanocomposite PVD coating (AlWiN XC), consisting of a CrAlSiN base layer combined with a TiC/C low-friction layer, deposited on Orvar 2M hot-work tool steel under ambient sliding conditions. Ball-on-disc tests conducted under technically dry friction with a Si_3N_4 ceramic counterbody enabled a direct comparison between the coated and uncoated steel, with particular emphasis on quantitative wear-track geometry analysis. The results showed that uncoated Orvar 2M steel exhibited intensive abrasive wear accompanied by localized plastic deformation, resulting in wear-track depths of 14–20 µm and areas of 8000–12000 µm². In contrast, the presence of the AlWiN XC coating limited the maximum wear depth to 2–7 µm and reduced the wear-track area to 1400–3000 µm², demonstrating a substantial reduction in wear intensity and indicating a modification of the sliding contact conditions associated with the load-bearing properties of the coating. Microscopic analyses suggest a transition in the wear mechanism from more unstable abrasive–adhesive behavior to a milder tribological regime dominated by micro-cutting. The coated samples also exhibited narrower and shallower wear tracks, which may correspond to reduced localized plastic deformation and a smaller real contact area. These observations are based on representative scans and should be interpreted qualitatively. Overall, the results demonstrate that the AlWiN XC coating enhances the wear resistance of Orvar 2M steel and modifies the contact geometry under the tested conditions.. These findings support the following conclusions:

- The AlWiN XC coating significantly improves the wear resistance of Orvar 2M steel at ambient temperature.
- The maximum wear depth was reduced by a factor of 3–5, and the wear track area decreased by 3–4 times, indicating a clear reduction in surface degradation.
- Application of the AlWiN XC coating is associated with changes in the wear mechanism and contact geometry, with trends suggesting a more uniform distribution of surface interactions.
- Observations suggest that the coating may limit severe localized damage, although the extent of stress distribution and crack mitigation cannot be fully quantified from the current data.
- The results confirm that the AlWiN XC coating is an effective surface modification strategy that improves the apparent reliability of tool steels under the tested tribological conditions.
- The coating appears to shift the wear mechanism toward a milder micro-cutting regime, reducing the extent of material transfer observed in uncoated samples.

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