

Tribological performance of Orvar 2M tool steel coated with ALWIN XC for improved forging tool durability

Research Article

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Abstract: This study presents a comprehensive evaluation of the tribological performance of hot-work tool steel Orvar 2M in its uncoated state and after surface modification with a hard physical vapor deposition (PVD) ALWIN XC coating, intended for hot forging applications. The research followed a sequential experimental approach, combining preliminary laboratory tests, advanced high-temperature tribological tests, and industrial verification. Preliminary dry-abrasive wear tests at room temperature were performed for both uncoated and coated variants. These tests provided an initial comparative assessment of abrasive wear resistance and allowed identification of dominant surface degradation mechanisms. The uncoated steel exhibited localized abrasive wear, including microcracks and scratches, while the ALWIN XC coating significantly reduced material loss and stabilized the wear process. For a more representative analysis, ball-on-disc tests were conducted at 200°C, corresponding to the operational temperature of forging tools. The ALWIN XC coating demonstrated a stable coefficient of friction and low wear rate. Scanning electron microscopy observations and energy dispersive X-ray spectroscopy analyses enabled correlation of microstructural and chemical changes with the main degradation mechanisms. Industrial-scale forging trials confirmed that coated tools achieved more than a twofold increase in lifespan compared to uncoated steel. The results demonstrate the reliability and relevance of the applied tribological testing methodology as a predictive tool for tool durability. These findings also support the further development and optimization of PVD-coated forging tools for enhanced service life under industrial conditions.

Keywords: Hot-work tool steel • PVD ALWIN XC coating • Tribological testing • Abrasive wear • Hot forging

1. Introduction

Wear studies of tool materials intended for hot die forging have been an important area of interest for both academia and industry for many years, due to the direct impact of wear resistance on tool life, process stability, and production costs. The literature emphasizes that the working conditions of forging tools are exceptionally complex, involving the simultaneous action of high temperatures, cyclic mechanical loads, intense friction, and contact with hot, often oxidizing charges [1–3]. For this reason, wear resistance studies employ tribological tests over a wide temperature range – from ambient conditions through intermediate temperatures to high-temperature tests – which

allow partial replication of the actual operating conditions of tools in forging processes [4–6]. Tests conducted at room temperature are commonly used for preliminary characterization of tool materials, enabling evaluation of their resistance to micro-abrasion, susceptibility to adhesive wear, and friction coefficient behavior under controlled sliding contact conditions [2,7]. Although these tests do not directly replicate hot forging conditions, they provide a valuable reference point for comparative analyses and allow identification of differences arising from microstructure, chemical composition, and the heat treatment state of the material.

Wear studies conducted at elevated and high temperatures, typically in the range of 200–600°C and above, are far more relevant for analyzing materials used in die forging, as additional degradation mechanisms characteristic

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of forging tool operation are activated [5,8,9]. The literature indicates that tribological tests at intermediate temperatures (200–400°C) enable analysis of friction coefficient stability, initial oxidation processes, and the influence of martensitic structure tempering on wear intensity [6,10]. High-temperature tests, performed using methods such as ball-on-disc, pin-on-disc, or block-on-ring, allow identification of complex wear mechanisms occurring under conditions approaching hot forging, including abrasion, adhesion, tribo-oxidation, and thermomechanical fatigue [8,11,12]. Numerous studies have shown that at elevated temperatures, the wear behavior changes significantly – from micro-abrasion dominance at low temperatures to complex processes involving formation and destruction of oxide layers, local material softening, and initiation of microcracks in the surface layer [9,13,14]. Consequently, it is emphasized that studies should be conducted over various temperature ranges and include both quantitative analyses (volumetric wear, friction coefficient) and qualitative assessments (wear track morphology, microstructural analysis), which together enable a more reliable evaluation of the wear resistance of tool materials [11,15].

In parallel with experimental studies, comparative analyses are developed to evaluate the tribological behavior of different hot work tool steels, such as H11, H13, WLV, or modern alloy-modified steels, with respect to temperature, load, and contact duration [9,16]. Authors consistently note that interpreting and comparing wear test results require particular caution, as test parameters – such as normal load, sliding speed, test temperature, counterbody geometry, or atmosphere – significantly influence the activation of specific wear mechanisms [7,17]. Therefore, the need for standardization of test procedures and referencing results to tribological standards, such as ASTM G99 or ISO 7148, is increasingly emphasized, as this enables more objective comparisons of materials intended for high-temperature operation [17,18]. A key element of modern studies is also the correlation of tribological results with material microstructure, including the analysis of tempering state, carbide morphology, and changes in the surface layer under thermomechanical loads [11,19,20]. This approach improves understanding the sources of differences in wear resistance between materials and provides a basis for more reliable prediction of tool behavior under actual forging conditions.

The service life of forging tools is directly related to the resistance of the core material and protective coatings to wear mechanisms occurring in hot die forging processes, such as micro-abrasion, adhesive wear, or high-temperature oxidation [21]. Laboratory tribological tests, including

ball-on-disc tests, allow quantitative evaluation of these mechanisms and enable prediction of tool service life, as wear tracks formed during laboratory tests often reflect degradation processes occurring under real operating conditions [22,23]. Wear tests simulating forging process conditions are particularly reliable at low and moderate temperatures, where micro-abrasion – common at the initial stages of die degradation – dominates. Theoretical and experimental studies reported by Holmberg and Matthews [20], Stachowiak and Batchelor [21], and Pawlak et al. [22] indicate correlations between micro-abrasion, adhesion, and the formation of tribochemical layers in metal-coating and metal-metal contacts. In previous studies [24,25], authors applied ball-on-disc tests to evaluate the wear of commercial cutting tools, whereas Sadeghi et al. [26] demonstrated the effectiveness of selected coatings in reducing micro-abrasion and adhesion under laboratory conditions. The application of physical vapor deposition (PVD) coatings, such as AlCrN, AlTiN, or AlCrSiN, significantly enhances the service life of forging tools by reducing surface wear and stabilizing the friction coefficient at elevated temperatures [27]. The literature shows that tools coated with modern coatings exhibit prolonged life, fewer surface defects, and better reproducibility of forging process parameters compared to uncoated tools [28]. On the other hand, tribological studies and coating investigations (e.g., hybrid PVD layers combined with thermochemical treatment) indicate that appropriately selected coatings or protective layers can substantially increase tool resistance to both abrasive and adhesive wear, as well as delay oxidation and surface cracking [29]. Contemporary research on the durability of dies and tools for hot die forging demonstrates that tool wear primarily results from a combination of mechanisms such as abrasion, adhesion, thermal oxidation, and thermomechanical fatigue. Analyses conducted on actual dies have shown that tools made of tool steels often achieve a service life ranging from several hundred to tens of thousands of forgings, with surface degradation – scratches, cracks, adhesion of the charge, and plastic deformation – being the main cause of failure [30,31]. Therefore, laboratory tribological tests constitute a justified and reliable means for preliminary assessment of the wear resistance of tool materials and surface modifications, enabling identification of dominant degradation mechanisms at a relatively low cost [32–34].

The aim of this study is a comparative evaluation of the tribological resistance and identification of wear mechanisms of Orvar 2M tool steel in the uncoated state and surface-modified with PVD ALWIN XC, intended for hot forging tools, using sequential laboratory tests and their verification under industrial conditions.

2. Materials and methods

The study was conducted to provide a preliminary analysis of wear mechanisms and a comparative evaluation of the tribological resistance of materials used for hot forging tools. The following material variants were analyzed:

- **Orvar 2M** – hot work tool steel in the uncoated state,
- **Orvar 2M + AlWIN XC** – Orvar 2M steel surface modified with a hard PVD coating.

The research program included the sequential application of laboratory methods followed by industrial verification:

- **Dry abrasive test** conducted at room temperature, serving as a preliminary assessment of abrasive wear resistance and identification of the dominant degradation mechanisms for both material variants.
- **Ball-on-disc tribological tests** performed at 200°C, enabling evaluation of the tribological behavior of the material and coating under elevated temperature conditions.

The applied laboratory tests, particularly the dry abrasive tests performed at room temperature, do not fully replicate the actual conditions of hot forging processes, where higher temperatures and different wear mechanisms occur. Nevertheless, they serve as preliminary studies and allow a comparative assessment of the abrasive wear resistance of the analyzed material variants, providing a reference point for interpreting results obtained under industrial conditions.

2.1 Dry abrasive test

A preliminary evaluation of the abrasive wear resistance of the tested materials was conducted using the dry abrasive test method. The tests were carried out on the T-07 Tester (MCNEMiT) test setup, shown in Figure 1.

The dry abrasive test serves as a reference method for assessing the wear of tool materials operating under

conditions of intensive interaction with abrasive particles, characteristic, among others, of ceramic forming processes. In the experiments, corundum No. 90 with a hardness of 9 on the Mohs scale was continuously supplied to the contact zone between the tested sample and a rotating rubber disc with a diameter of $d = 50$ mm. The sample was pressed against the disc surface with a constant normal force, while the disc's rotational speed and the test duration (corresponding to a specified number of revolutions) remained constant for all measurement series. The criterion for evaluating abrasive wear resistance was the sample's mass loss, determined as the difference in mass before and after testing. Based on the obtained results, the relative abrasive wear resistance K_b was determined as follows:

$$K_b = \frac{Z_{ww} \cdot \rho_b \cdot N_b}{Z_{wb} \cdot \rho_w \cdot N_w}, \quad (1)$$

where Z_{ww} is the mass loss of the reference sample (g); Z_{wb} is the mass loss of the tested material (g); ρ_w is the density of the reference material; ρ_b is the density of the tested material; N_w is the number of revolutions of the sliding path of the reference sample; and N_b is the number of revolutions of the sliding path of the tested sample.

The duration of the dry abrasive test was selected depending on the resistance of the tested materials to abrasive wear, so as to obtain a measurable mass loss of the sample. For most materials, a testing time corresponding to 1,800 revolutions of the rubber roller was applied, whereas for samples with increased wear resistance, the test duration was extended. The reference material was C45 steel, for which – according to the test methodology – a shortened test time corresponding to 600 roller revolutions was applied. The mass loss of the reference sample served as the basis for determining the relative abrasive wear resistance coefficient K_b for the other materials.

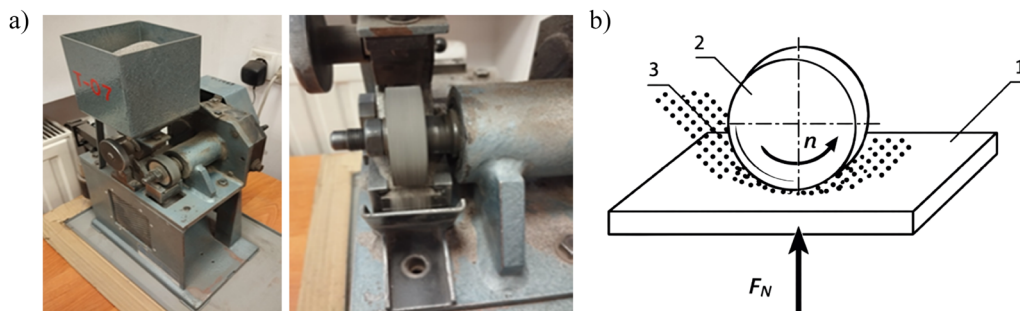


Figure 1. Dry abrasive test setup T-07: (a) Photo of the testing and measurement apparatus and (b) test concept: 1 – test sample, 2 – rubber roller, and 3 – electrocorundum.

2.2 Wear resistance testing using the ball-on-disc method

Wear resistance tests were conducted using the ball-on-disc method with a DUCOM tribometer (ball-disc configuration) under technically dry friction conditions. The analyzed pairing included:

- a Si_3N_4 ball,
- a disc made of Orvar 2M steel coated with PVD ALWIN XC.

The tests were carried out at an elevated temperature of 200°C, achieved by induction heating of the disc (Figure 2). For each sample, a single wear test was performed, recording the friction force, which allowed the determination of the coefficient of friction. The test parameters and the wear track geometry are presented in Table 2.

After completing the tests, a microscopic analysis of the wear tracks was conducted:

- optical microscopy and scanning electron microscopy (SEM) (magnifications of 50–100×) to identify the morphology of the wear traces,
- scanning of the wear track topography in three areas distributed approximately every 120° using a Talysurf CCI interferometric microscope, and
- analysis of 2D profiles and 3D topography in MountainsMap Universal software, enabling the determination of maximum wear depths and volumetric wear.

Based on the topographical data, the volumetric wear Z_{obj} and the wear index, which accounts for the load and sliding distance, were calculated. The calculations of volumetric wear and the wear index W_z for the tested samples were performed using equations (2) and (3).

$$W_z = \frac{Z_{\text{obj}}}{F \cdot s} \left[\frac{\text{m}^3}{\text{N} \cdot \text{m}} \right], \quad (2)$$

where W_z is the wear index, Z_{obj} is the volumetric wear determined for the entire abrasive wear track, F is the load, and s is the sliding distance.

$$Z_{\text{obj}} = P_{\text{A5r}} \cdot \text{Obw} [\text{m}^3], \quad (3)$$

where Z_{obj} is determined for the entire abrasive wear track, P_{A5r} is the average value of the cross-sectional areas of the track measured in three regions, and Obw is the circumference of the abrasive wear track.

Additionally, a chemical composition analysis of the wear tracks was performed using SEM/energy dispersive X-ray spectroscopy (EDS), enabling qualitative identification of elements in the tribological contact area.

3. Results and discussion

3.1 Dry abrasive

Based on the conducted measurements, the results are presented in Table 1. The table summarizes the values of average mass loss, material density, the number of revolutions applied in the test, and the calculated relative abrasive wear resistance coefficient K_b for all investigated material variants.

Analysis of the results indicates that C45 steel, used as the reference sample, exhibited a mass loss of 0.062 g after 600 roller revolutions, serving as the baseline for determining the K_b value of 1.000. These results are presented graphically in Figure 3, showing a comparison of the relative abrasive wear resistance K_b for all tested material variants. In the case of Orvar 2M steel in the uncoated condition, after 1,800 revolutions, an average mass loss of 0.155 g was recorded, corresponding to a relative resistance K_b of 1.188, indicating a slight improvement compared to the reference steel despite the longer friction time. The application of a PVD ALWIN XC coating on the Orvar 2M steel surface significantly enhanced the material's resistance to abrasive wear.

For the same test duration as for the uncoated material (30 min, 1,800 revolutions), an almost negligible mass loss (0.001 g) was recorded, within the measurement error, resulting in an extremely high K_b value of 184.107. Extending the test duration to 60 min (3,600 revolutions) led to the appearance of noticeable wear (0.02 g), with a

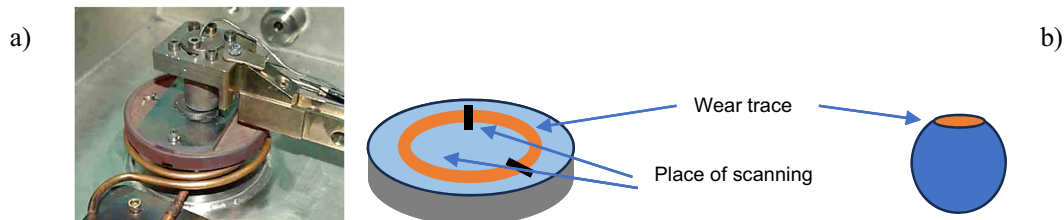


Figure 2. View of (a) DUCOM tribotester and (b) schematic of wear tracks on the disc and ball indicating the analyzed locations.

Material	Wear – average value (g)	Density (g/cm ³)	Rotations	Coefficient K_b
C45 (reference sample)	0.062	7.86	600	1.000
Orvar 2M	0.155	7.78	1,800	1.188
Orvar 2M + AlWIN 30 min	0.001	7.78	1,800	184.107
Orvar 2M + AlWIN 60 min	0.02	7.78	3,600	18.411

Table 1. Dry abrasive test results for the tested materials.

Conditions/test no.	Disc temperature T (°C)	Test duration t (s)	Sliding distance s (m)	Load F (N)	Rotational speed v (m/s)	Wear track radius r (m)
Test 1	200	5,000	500	10	0.1	0.006

Table 2. Tribological test parameters.

corresponding K_b value of 18.411, which still represents a significant improvement compared to the uncoated steel.

Additionally, a detailed surface analysis of the samples was conducted, allowing identification of the dominant wear mechanisms. Representative surface profiles are shown in Figures 4 and 5.

By analyzing the depth of the indentation on the wear profile after the tests, an average depth of 0.27 mm was obtained for the Orvar 2M samples. For the Orvar 2M + AlWIN XC samples, an average depth of 0.052 mm was measured after 1,800 revolutions (30 min) and 0.004 mm after 60 min (3,600 revolutions). A preliminary analysis of wear and wear mechanisms was also conducted on the samples after testing (Figure 6).

Observations and analyses based on the above profiles and macroscopic images revealed that:

- Orvar 2M sample (uncoated) – the main degradation mechanism was mechanical abrasion and surface scratching. Wear traces were unevenly distributed along the contact path between the sample and the roller. The surface profile indicates the formation of micro-cracks, grooves, and fine scratches resulting from the aggressive action of electrocorundum, typical of “grooving” type abrasive wear. Wear was concentrated locally in areas of highest contact, which could lead to accelerated tool degradation in industrial practice (Figure 6c).
- Orvar 2M + AlWIN XC sample – after 30 min of testing (Figure 6b; sample no. 3), the surface remained practically intact. Microscopic observations revealed no grooves or microcracks, confirming the high hardness of the coating and its effective protection of the substrate against abrasion by electrocorundum. After extending the test duration to

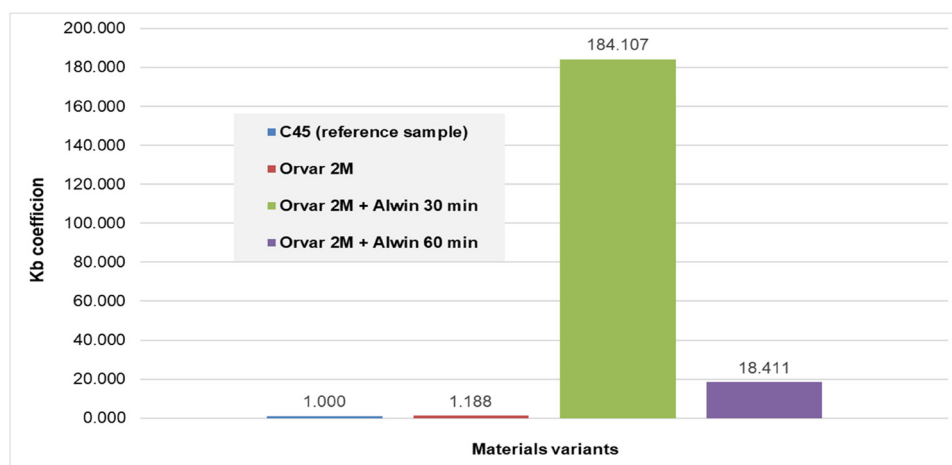


Figure 3. Comparison of dry abrasive test results – relative abrasive wear resistance K_b .

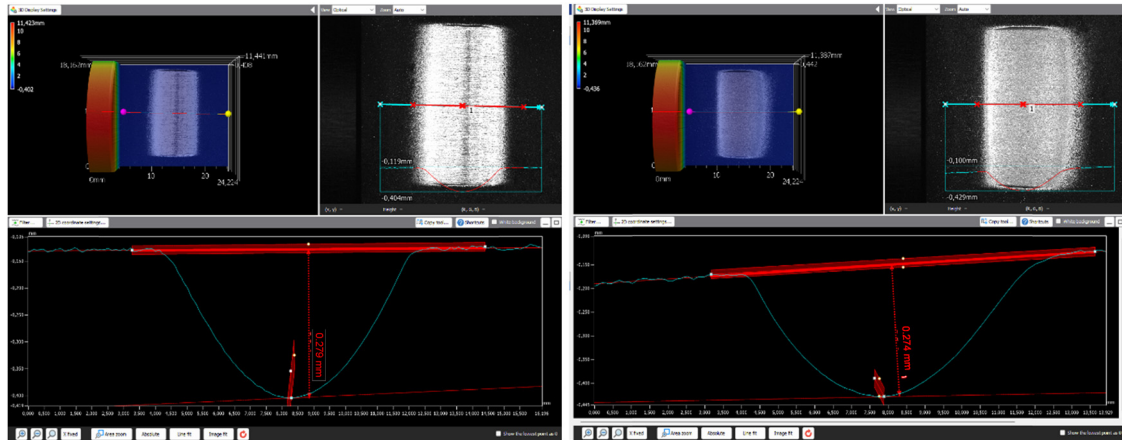


Figure 4. Surface profile of the Orvar 2M sample after 30 min of testing in the dry abrasive test for two selected specimens.

60 min, limited and localized coating damage was observed in the form of initial microcracks and local spallation of the PVD layer (Figure 6d). With increasing exposure time, these defects gradually developed into larger grooves and localized coating detachment. The character and distribution of the wear traces indicate that the ALWIN XC coating effectively disperses contact stresses and homogenizes surface loading, thereby delaying intensive degradation and limiting damage transfer to the substrate. The relatively uniform distribution of wear marks further suggests reduced susceptibility to local surface overloads. Analysis of wear profiles and surface traces shows that the dominant degradation mechanism for the uncoated material was localized sliding abrasion accompanied by surface scratching. In contrast, for the coated samples, the prevailing mechanism was the initiation of microcracking within the coating, which only under prolonged testing led to minor volumetric wear. Preliminary room-temperature tests showed that uncoated Orvar 2M steel undergoes pronounced localized

abrasive wear, including microcracks, grooves, and fine scratches, dominated by mechanical abrasion and surface scratching. In contrast, the PVD ALWIN XC coating markedly improved wear resistance: after 30 min, wear was nearly negligible, while after 60 min, only limited, evenly distributed coating damage in the form of microcracks and local PVD layer detachment was observed, without significant substrate involvement. These findings indicate effective stress dispersion by the coating and justify further ball-on-disc investigations at approximately 200°C, corresponding to forging tool operating conditions, to assess coating durability and wear mechanisms under conditions closer to service.

3.2 Ball-on-disc – microscopic analysis of wear tracks on balls and discs

Microscopic analysis of the wear tracks on Si_3N_4 balls and Orvar 2M steel discs coated with ALWIN XC, conducted

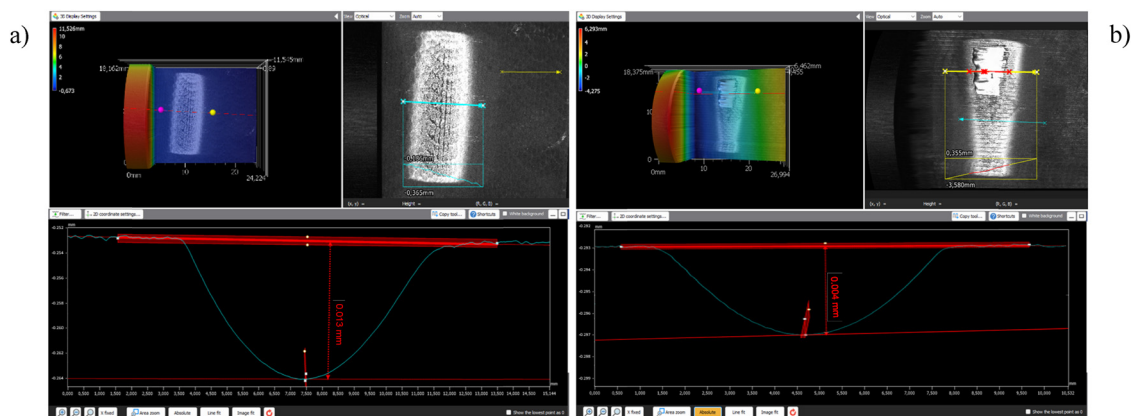


Figure 5. Surface profile of the Orvar 2M + ALWIN sample after: (a) 30 min of testing in a dry abrasive and (b) 60 min of tests.

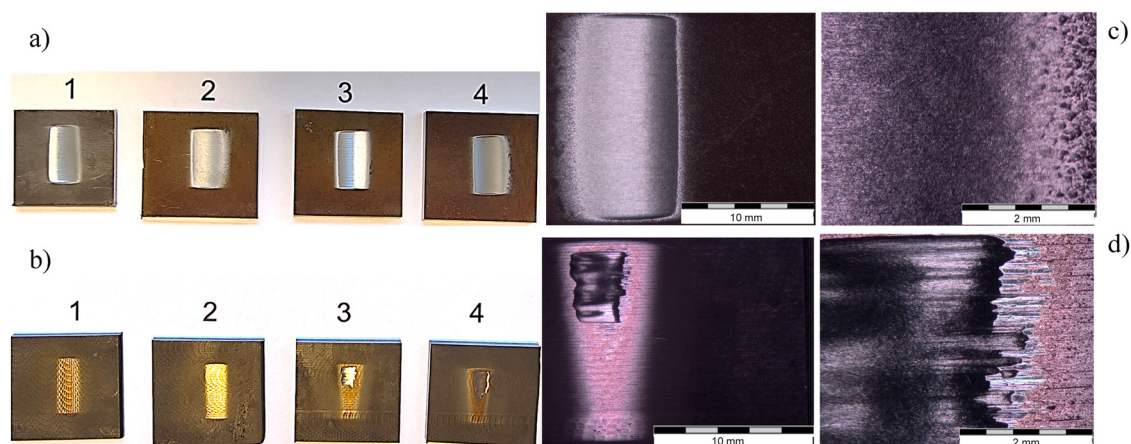


Figure 6. Surface morphology of the samples after tribological testing: (a) Orvar 2M steel (sample nos 1–4), (b) Orvar 2M steel with ALWIN XC coating (sample nos 1–4), (c) detailed view of sample no. 4 (noncoated-only Orvar 2M), (d) detailed view of sample no. 4 (Orvar 2M + ALWIN_XC); numbers 1–4 denote individual test samples; scale bars are indicated in the detailed images.

after ball-on-disc tests at 200°C, enabled assessment of the nature and uniformity of the wear processes in the examined tribological system (Figure 7). The main test parameters are shown in Table 2.

Regular, circular wear tracks with homogeneous morphology, typical of stable sliding friction conditions, were observed on the surfaces of the Si_3N_4 balls. The measured diameters of the wear tracks for three repetitions of the test at 200°C were 1.174, 0.903, and 0.816 mm, respectively, indicating a moderate scatter of results due to local variations in contact conditions and surface microgeometry. Analysis of the disc surfaces revealed continuous and uniform wear tracks along the entire circumference of the wear path, without cracks, deep scratches, or local material loss. The

observed track areas exhibited similar morphology, indicating a uniform wear process and stable performance of the ALWIN XC coating under the tested temperature conditions. The dominant wear mechanisms were microscopic abrasive processes, with localized contributions from adhesive interactions. The absence of signs of severe surface degradation indicates effective protection of the steel substrate by the coating and moderate intensity of tribological interactions at 200°C. Subsequently, 3D scanning of the wear paths was performed. Measurement sheets of the wear tracks, including three-dimensional surface scans, cross-sectional profiles, and geometric parameters of the wear tracks, are presented for three selected areas of the disc surfaces (Figure 8).

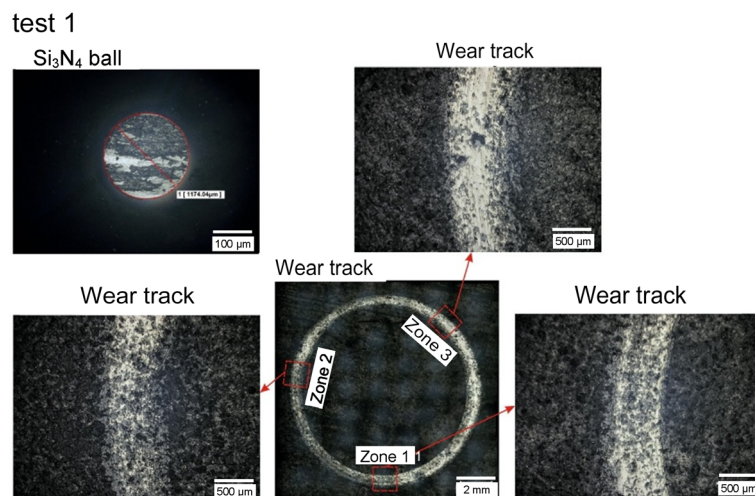


Figure 7. Microscopic observations of wear tracks on the ball and disc after the ball-on-disc test at 200°C.

Analysis of the three-dimensional topography of the wear tracks in three selected areas allowed assessment of wear uniformity and identification of the actual tribological contact zone. The cross-sectional profiles exhibited regular and repeatable patterns, without local topography disturbances, indicating a stable friction process and no local wear-through of the ALWIN XC coating to the steel substrate. The determined maximum track depths and cross-sectional areas formed the basis for calculating volumetric material loss and for further determination of the wear indicators Z_{obj} and W_z .

3.2.1 Results of abrasive wear tests of the ALWIN XC coating

The tribological tests enabled a quantitative assessment of the abrasive wear intensity of the ALWIN XC coating as a function of test temperature. The main scope of the present study focuses on tests conducted at 200°C, for which a

detailed microscopic analysis of the wear tracks and their geometric parameterization was performed (Table 3). The obtained values of the Z_{obj} and W_z indicators indicate wear of the coating under stable abrasive conditions, without complete removal of the protective layer. Additional tests performed at 400 and 600°C constitute a separate research stage and are presented here solely for comparative purposes, providing a better illustration of the effect of temperature on wear intensity. For these higher temperatures, wear track images and detailed analyses of surface degradation mechanisms are not presented and will be addressed in further, in-depth studies and subsequent publications.

The data in Table 3 show a clear increase in the abrasive wear intensity of the ALWIN XC coating with increasing tribological test temperature. Despite the shorter sliding distance at 400 and 600°C (150 m) compared to 200°C (500 m), a significant increase was observed in both volumetric wear and the wear index. The W_z value

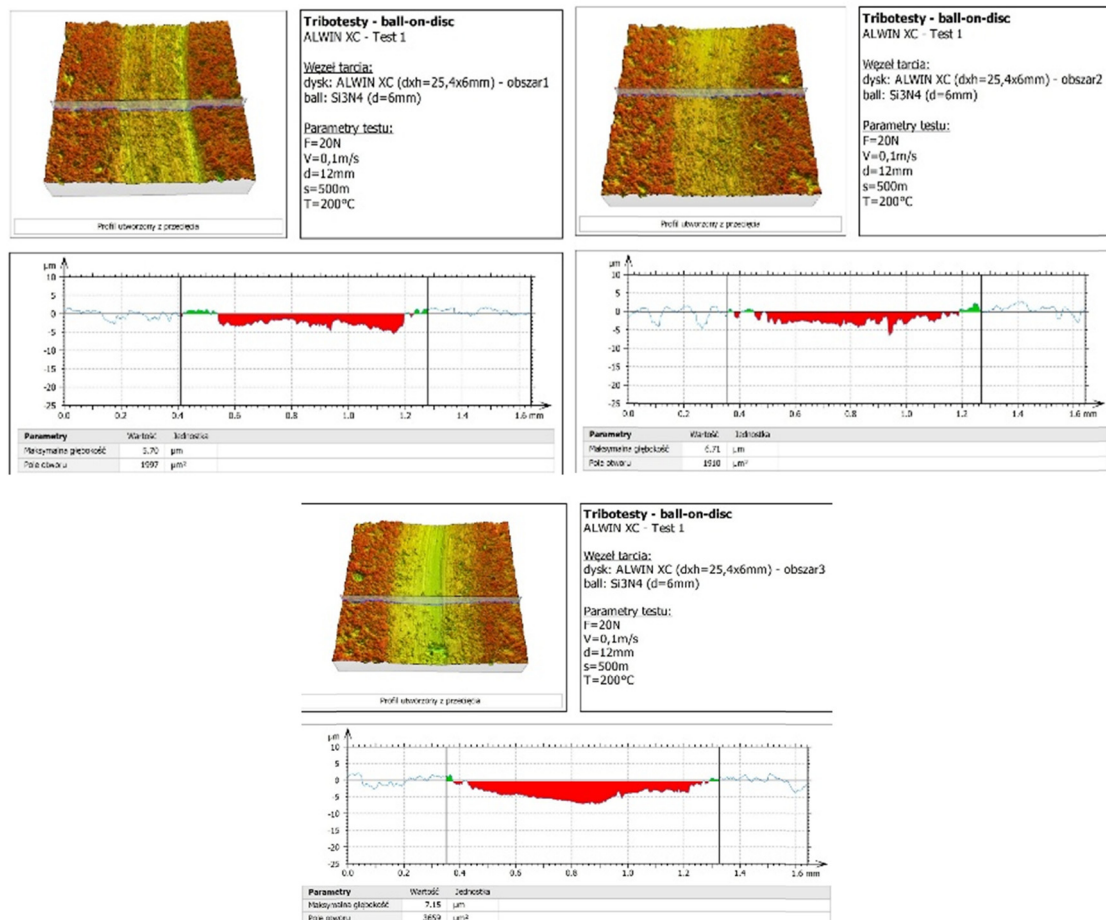


Figure 8. Measurement sheets from 3D scanning of selected areas of the sample after the ball-on-disc test at 200°C for three zones.

Test no.	Temperature T (°C)	Sliding distance S (m)	Volumetric wear Z_{obj} (m ³)	Wear index W_z (m ³ /N·m)
Test 1	200	500	9.51×10^{-11}	9.51×10^{-15}
Test 2	400	150	1.06×10^{-10}	3.53×10^{-14}
Test 3	600	150	1.67×10^{-10}	5.57×10^{-14}

Table 3. Summary of abrasive wear results from the tribological tests.

increased from 9.51×10^{-15} m³/(N/m) at 200°C to 3.53×10^{-14} m³/(N/m) at 400°C and 5.57×10^{-14} m³/(N/m) at 600°C, corresponding to nearly fourfold and sixfold increases, respectively. A similar trend is observed for Z_{obj} , which rises from 9.51×10^{-11} m³ to 1.06×10^{-10} m³ and 1.67×10^{-10} m³. The wear index obtained for Orvar 2M steel coated with the ALWIN XC system (9.51×10^{-15} m³/N/m) is approximately two times lower than the wear rates reported in the literature for uncoated steels of the H13 group tested at around 200°C, which are in the range of $2\text{--}2.3 \times 10^{-14}$ m³/N/m [32–34]. These results indicate progressive degradation of the coating's top layer with increasing temperature, even over a limited sliding distance.

The increase in wear intensity can be attributed to the weakening of the coating's mechanical properties at higher temperatures, greater susceptibility to micro-abrasion, and changes in the characteristics of the tribochemical layer, with the observed degradation mechanisms including microcracking, spalling, and material adhesion. Detailed analysis of the wear mechanisms at 400 and 600°C, however, requires further microstructural and tribological studies. Figure 9 shows the friction coefficient during test.

After the ball-on-disc test at 200°C, Orvar 2M steel coated with Alwin XC exhibited a stable coefficient of friction, with an average value in the range of 0.40–0.48. This

level of friction indicates good tribological stability of the coating at elevated temperature, with no evidence of sudden degradation phenomena during the test.

Cross-sectional microstructural analysis of Orvar 2M Supreme steel (~48 HRC) with ALWIN XC coating after the ball-on-disc test at 200°C (Test 1) confirmed high coating–substrate stability (Figure 10).

Observations of the metallographic cross-sections at 200× and 500× magnifications revealed a continuous uniform coating layer of relatively constant thickness, without signs of advanced delamination, severe cracking, or local spalling. The interface between the ALWIN XC coating and the steel substrate remained distinct and continuous, indicating excellent adhesion after tribological exposure at 200°C. Minor localized voids beneath the coating were observed, but they did not form continuous weak zones and were also present outside the wear track.

The ALWIN XC coating, with a hardness above 4,000 HV, provides high resistance to mechanical abrasion. The TiC interlayer, characterized by low friction and high hardness, reduces local shear stresses and limits adhesion of the counter material. Consequently, the dominant wear mechanisms are mild, limited to microscopic surface abrasion and occasional small-scale coating detachment, without compromising the integrity of the functional layer

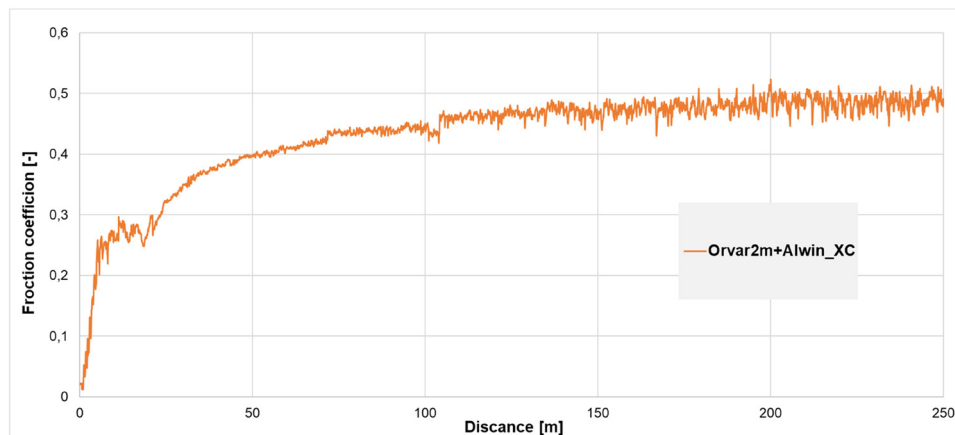


Figure 9. Coefficient of friction for Orvar 2M steel with ALWIN XC coating at 200°C.

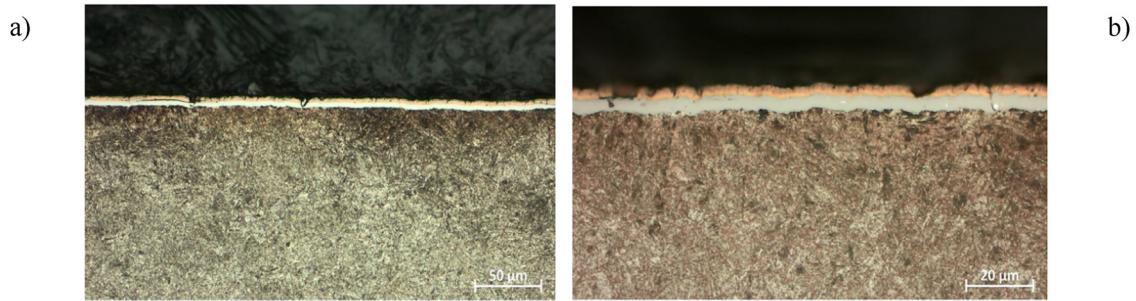


Figure 10. Metallographic cross-section of the sample (ball-on-disc, 200°C), etched: (a) 200× magnification, (b) 500× magnification; Orvar 2M (1.2344) steel with nanocrystalline ALWIN XC coating and TiC interlayer.

or the substrate. The substrate microstructure across the examined section is homogeneous and typical for tempered 1.2344 steel, consisting of tempered martensite with uniformly distributed carbide precipitates. No white layer or local microstructural changes indicating overheating or severe thermomechanical effects were observed. Minor non-metallic inclusions were present but did not significantly affect wear behavior under the tested conditions. These results confirm that at 200°C, the Orvar 2M (48 HRC)/ALWIN XC coating with TiC interlayer exhibits high tribological stability. The high coating hardness and TiC properties limit local stresses and shear, resulting in mild wear mechanisms that do not cause significant damage to the coating or substrate.

The Vickers hardness profile (HV0.1) as a function of distance from the worn surface for the Orvar 2M (1.2344) samples, heat-treated to approximately 48 HRC and coated with nanocrystalline ALWIN XC with TiC interlayer, is shown in Figure 11.

In the near-surface region of the samples, measured in three independent tests at 200°C, small local hardness fluctuations were observed: 652–694 HV0.2 in the first measurement, 655–697 HV0.1 in the second, and 650–695 HV0.2 in the third. Deeper into the material, the hardness profile gradually stabilizes, reaching approximately 650–670 HV0.2 at a depth of 1 mm, corresponding to the characteristics of tempered martensite in H13 steel.

It should be noted that the hardness of the ALWIN XC coating itself is not reported, as its thickness of only a few micrometers prevents accurate measurement using the HV0.1 microhardness method, despite the coating remaining undamaged and unworn. The hardness distributions indicate that the ALWIN XC coating with the TiC interlayer does not introduce significant local stresses or microstructural changes in the near-surface zone. Minor fluctuations in HV0.2 values can be attributed to natural variations in the tempered martensite microstructure and localized tribological effects. These results confirm high

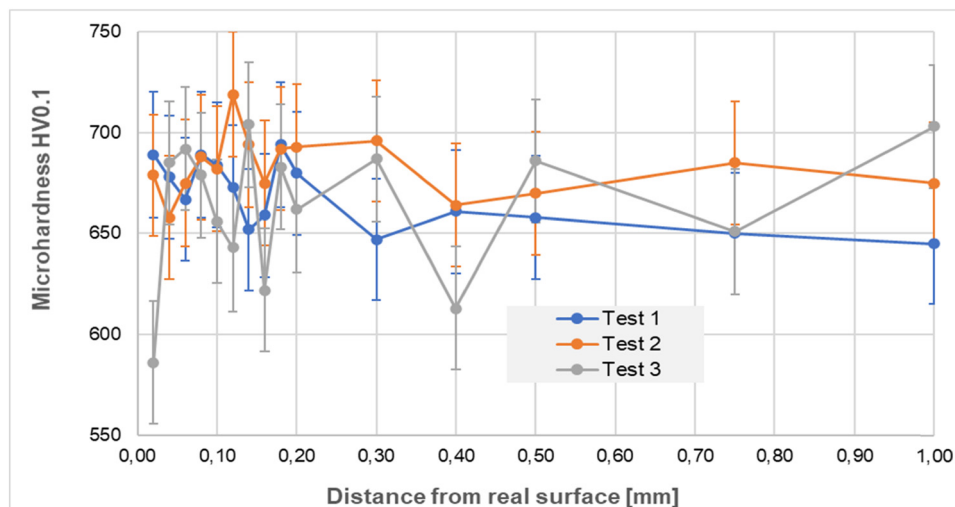


Figure 11. HV0.1 hardness distributions on cross-sections after the ball-on-disc test.

uniformity of mechanical properties near the surface and stable hardness throughout the material after tribological exposure at 200°C. The small differences between measurements do not significantly affect the overall hardness profile, demonstrating effective substrate protection by the hard ALWIN XC coating and reduction in local shear stresses due to the TiC interlayer.

3.2.2 EDS analysis – Mapping of disc wear tracks

To understand the wear mechanisms of the ALWIN XC coating, elemental distribution on the surface of the wear tracks was analyzed. EDS maps allow identification of local changes in chemical composition, highlighting areas of intense wear and contact with the steel substrate.

EDS analysis of the wear track surfaces on the ALWIN XC coating of the Orvar 2M sample after the ball-on-disc test at 200°C revealed local chemical composition changes in regions of more intensive tribological contact. The presence of iron (Fe) indicates exposure and wear-through of

the coating to the steel substrate, while the absence of titanium (Ti) in selected areas confirms complete removal of the top coating layer. Elemental distributions indicate a heterogeneous degradation pattern, involving micro-cracking, spalling, and material adhesion, allowing correlation of local chemical changes with the dominant wear mechanisms in the tribochemical layer (Figure 12).

The obtained observations serve as a reference for comparison with the ball results, allowing assessment of the influence of contact geometry and tribological load on local coating degradation mechanisms.

3.2.3 EDS analysis – Mapping of ball wear tracks

To evaluate local tribochemical interactions in the ball-coating contact, EDS maps of wear tracks on the Si_3N_4 ceramic ball were obtained after the ball-on-disc test at 200°C (Figure 13). Analysis of these maps allows identification of material transfer from the ALWIN XC coating to the ball surface and enables correlation of the observed

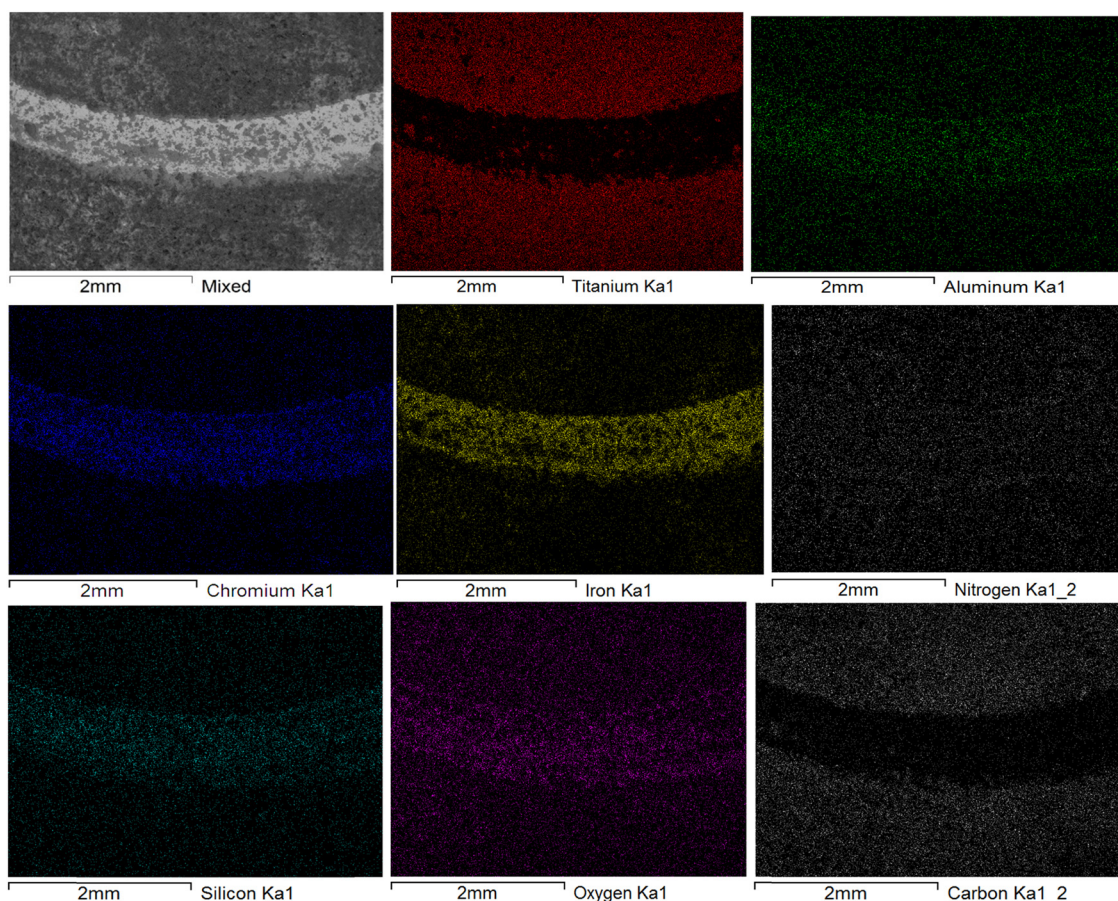


Figure 12. Compilation of EDS mapping of the disc wear track (Test 1, 200°C).

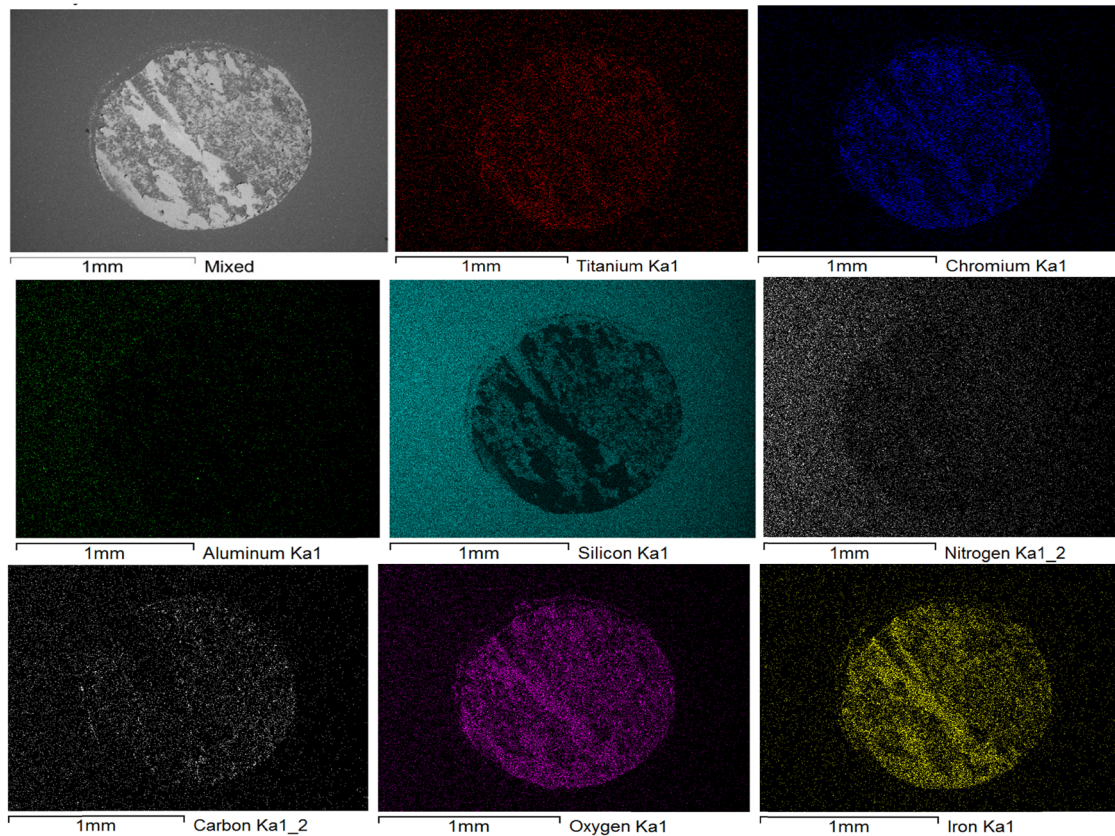


Figure 13. Compilation of EDS mapping of the ball wear track (Test 1, 200°C).

chemical changes with degradation of the disc, which is the primary focus of the study.

EDS maps revealed the presence of Ti, Cr, and Fe on the ball surface, indicating both wear of the ALWIN XC coating and material transfer onto the ball. Compared with observations for the disc, where local coating removal and exposure of the steel substrate were the main degradation mechanisms, the ball primarily shows signs of adhesion and accumulation of coating material, reflecting the directional nature of the tribological contact. Elemental distributions and bright areas on the EDS maps indicate heterogeneous wear, combining microcracking, spalling, and adhesion mechanisms, and allow correlation of material transfer with the dominant tribological mechanisms in the ball–coating contact.

3.2.4 SEM images of ball and disc wear tracks

The presented SEM images show the surface of the Si_3N_4 ceramic ball after the ball-on-disc tests with the ALWIN XC coating on the steel substrate. The observed wear tracks reflect the nature of the tribological contact, revealing

mechanical interactions between the ball and coating surfaces (Figure 14).

SEM images reveal numerous wear features, including localized coating wear, material spalling, and typical mechanical damage resulting from intensive frictional contact. The wear areas indicate local disruption of the coating continuity, while spalling may reflect its brittleness or microstructural heterogeneity. Additionally, observed fine scratches, edge cracks, and indentations suggest fatigue-related surface interactions during the test. Such features allow assessment of the ALWIN XC coating's wear resistance and identification of the dominant degradation mechanisms in the ball–coating contact, complementing the information obtained from the EDS maps.

4. Summary

This work presents a comprehensive study on the durability of Orvar 2M tool steel in its uncoated state and after surface modification with the hard PVD ALWIN XC coating, in the context of applications in hot forging processes. The

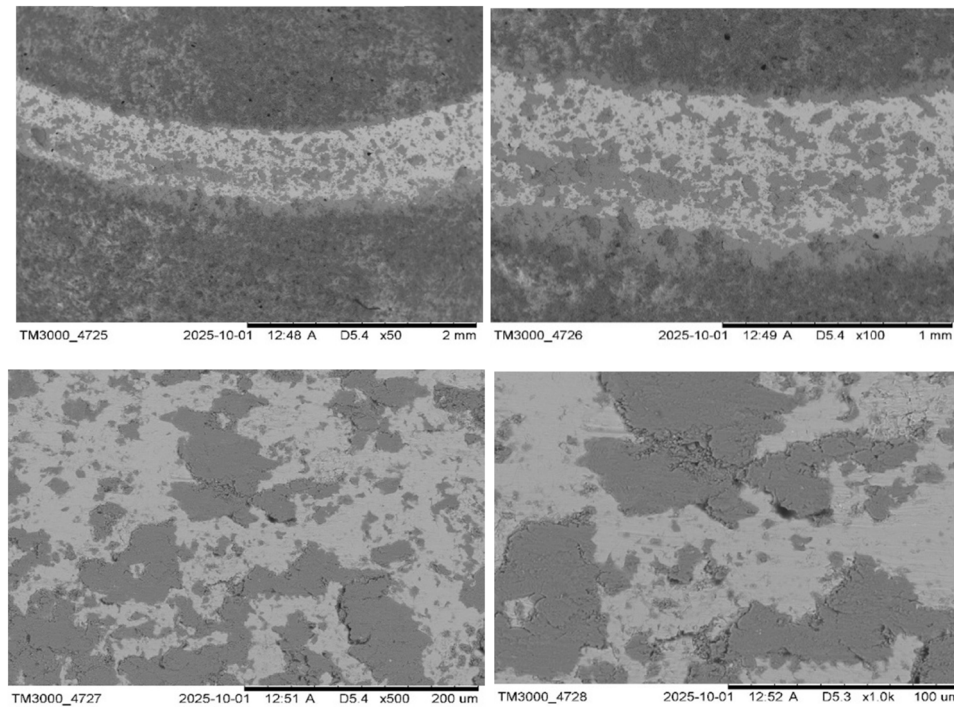


Figure 14. Surface microstructure after the tribological test. Areas of coating wear and mechanical damage – Test 1, 200°C.

research program included preliminary laboratory tests using dry abrasive wear at room temperature, as well as high-temperature ball-on-disc tests conducted at 200°C only. Preliminary tests at ambient temperature revealed that uncoated Orvar 2M steel undergoes localized abrasive wear, including microcracks, grooves, and fine scratches, with aggressive mechanical abrasion being the dominant degradation mechanism, as confirmed by wear profiles. The application of the AlWIN XC coating significantly enhanced material resistance: after 30 min of testing, wear was nearly negligible, and only after 60 min did minor, localized microcracks and small spalling appear, gradually progressing to larger grooves and PVD layer detachment, indicating effective stress dissipation and homogenization of surface loading by the coating.

Ball-on-disc tests at 200°C confirmed the high tribological resistance of the AlWIN XC coating, showing a stable coefficient of friction ($\mu = 0.4\text{--}0.48$) and a low wear rate ($W_z = 3.5 \times 10^{-14} \text{ m}^3/\text{N/m}$). SEM observations and EDS mapping revealed minimal surface wear, spalling, and secondary abrasive mechanisms, allowing correlation of chemical and mechanical changes with the dominant coating degradation processes. Measurements at elevated temperatures of 400 and 600°C, conducted over a shorter sliding distance (150 m), showed a clear increase in abrasive wear. The volumetric wear rate (W_z) increased from

$9.51 \times 10^{-15} \text{ m}^3/(\text{N/m})$ at 200°C to $3.53 \times 10^{-14} \text{ m}^3/(\text{N/m})$ at 400°C and $5.57 \times 10^{-14} \text{ m}^3/(\text{N/m})$ at 600°C, corresponding to nearly fourfold and sixfold increases, respectively. A similar trend was observed for the wear index (Z_{obj}), rising from $9.51 \times 10^{-11} \text{ m}^3$ to $1.06 \times 10^{-10} \text{ m}^3$ and $1.67 \times 10^{-10} \text{ m}^3$, indicating progressive increase in wear intensity with temperature.

In conclusion, the tribological laboratory studies demonstrated that the PVD AlWIN XC coating substantially enhances the wear resistance of Orvar 2M steel, increases the durability of the surface layer, and homogenizes contact stress distribution, ensuring high tribological stability at moderate temperatures and allowing identification of the dominant coating degradation mechanisms as a function of temperature.

4.1 Future research directions

The obtained laboratory results confirm the high tribological resistance of the PVD AlWIN XC coating on Orvar 2M steel under technically dry friction and at 200°C. Further research should include extended ball-on-disc tribological tests over a wider temperature range and under conditions including lubricants and coolants used in hot forging processes, enabling assessment of friction stability and

degradation mechanisms under conditions closer to real industrial operation.

It should be emphasized that the AlWIN XC coating was applied directly onto Orvar 2M steel without a nitrided layer, making the observed wear resistance particularly noteworthy. In the next stages of research, the application of an additional nitrided layer is planned, along with a comparative evaluation of its effect on tribological durability and resistance to thermomechanical loads, as well as verification of the results in tests conducted on actual forging tools.

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Author contributions

Marek Hawryluk was responsible for all aspects of the study, including conceptualization, methodology, validation, formal analysis, investigation, resources, data curation, writing – original draft preparation, writing – review and editing, visualization, supervision, and project administration.

Conflict of interest statement

The authors have no conflicts of interest/competing interests to declare that are relevant to the content of this article.

Ethics approval

The article follows the guidelines of the Committee on Publication Ethics (COPE) and involves no studies on human or animal subjects.

Data availability statement

The datasets and material generated and/or analyzed during the current study are available from the corresponding author on reasonable request.

References

- [1] Hutchings, I.M., Shipway, P., Tribology: Friction and wear of engineering materials, (2nd ed.), Butterworth-Heinemann, 2017
- [2] Tang, Z., Li, W., Yang, Z., Wang, J., Effect of solution and artificial aging heat treatment on the hardness, friction and wear properties of laser cladding and roll-formed 18Ni300 materials, *Mater. Sci.-Poland*, 2024, 42(2): 26–40. doi: 10.2478/msp-2024-0017
- [3] Roberts, G., Krauss, G., Kennedy, R., Tool steels, ASM International, 1998
- [4] ASTM International, ASTM G99–17: Standard test method for wear testing with a pin-on-disk apparatus, ASTM International, 2016
- [5] International Organization for Standardization, ISO 7148-1: Plain bearings – Tribological testing of bearing materials – Part 1: Determination of friction and wear properties of self-lubricating materials (ISO 7148), ISO, 1995
- [6] Hawryluk, M., Marzec, J., Lachowicz, M., Makuła, P., Nowak, K., Evaluation of the possibility of improving the durability of tools made of X153CrMoV12 steel used in the extrusion of a clay band in ceramic roof tile production, *Mater. Sci.-Poland*, 2023, 41(1): 94–109. <https://sciendo.com/pl/article/10.2478/msp-2023-0011>.
- [7] Straffelini, G., Friction and wear: Methodologies for design and control, Springer, 2015
- [8] Vergne, C., Boher, C., Wear of hot-work tool steels under sliding contact, *Wear*, 2006, 260(7–8): 789–797. doi: 10.1016/j.wear.2005.06.038
- [9] Podgornik, B., Leskovšek, V., High temperature wear mechanisms of tool steels, *Tribol. Int.*, 2010, 43(12): 2345–2352. doi: 10.1016/j.triboint.2010.06.004
- [10] Wang, L., Zhang, T., Li, X., Tribological behavior of hot-work tool steel under dry sliding, *Wear*, 2012, 292–293: 21–28. doi: 10.1016/j.wear.2012.07.009
- [11] Bay, N., Wanheim, T., Friction and wear in metal forming, *CIRP Ann.*, 1992, 41(2): 645–650. doi: 10.1016/S0007-8506(07)63277-5
- [12] Muro, M., Artola, G., Gorriño, A., Angulo, C., Wear and friction evaluation of different tool steels for hot stamping, *Adv. Mater. Sci. Eng.*, 2018, 2018: 3296398. doi: 10.1155/2018/3296398
- [13] Joun, M.S., Wear and durability of tool steels in hot forging processes. *J. Mater. Process. Technol.*, 2008, 205(1–3): 426–433. doi: 10.1016/j.jmatprotec.2007.11.030
- [14] Kovačević, L., Vilotić, D., Tribological performance of hot work steels, *Wear*, 2011, 271(1–2): 212–220. doi: 10.1016/j.wear.2010.09.005

- [15] Demir, M., Kanca, E., Karahan, I.H., Effect of saccharin addition on formation, wear and corrosion resistance of electrodeposited Ni-Cr coatings, *Mater. Sci.-Poland*, 2024, 41(3): 111–125, Wroclaw University of Science and Technology. doi: 10.2478/msp-2023-0036
- [16] Hawryluk, M., Dudkiewicz, Ł., Zwierzchowski, M., Polak, S., Lachowicz, M., Ziemba, J., et al., Influence of the nitriding process on the durability of tools used in the production of automotive forgings in industrial hot die forging processes on hammers, *Mater. Sci.-Poland*, 2024, 42(4): 113–130. doi: 10.2478/msp-2024-0047
- [17] ASTM International, ASTM G133 – Standard test method for linearly reciprocating ball-on-flat sliding wear, ASTM International, 2017
- [18] International Organization for Standardization, ISO 20808: Physical vapour deposition (PVD) coatings – Characterization (tribological properties), ISO, 2012
- [19] Zhang, S., Wang, L., Kong, H., Recent advances in PVD coatings for high-temperature tribological applications, *Surf. Coat. Technol.*, 2020, 385: 125430. doi: 10.1016/j.surfcoat.2020.125430
- [20] Holmberg, K., Matthews, A., *Coatings tribology: Properties, mechanisms, techniques and applications*, (2nd ed.), Elsevier, 2009
- [21] Stachowiak, G.W., Batchelor, A.W., *Engineering tribology*, (4th ed.), Butterworth-Heinemann, 2014
- [22] Pawlak, W., Urbaniak, W., Kulczyk, M., Influence of ceramic counterpart material on tribological behaviour of thin hard coatings, *Tribol. Int.*, 2019, 138: 111–120. doi: 10.1016/j.triboint.2019.01.045
- [23] Khadem, M., Jahanmir, S., High-temperature tribological behaviour of advanced PVD coatings: A review, *Wear*, 2021, 488–489: 204178. doi: 10.1016/j.wear.2021.204178
- [24] Holmberg, K., Friction and wear of coatings at elevated temperatures, *Tribol. Int.*, 2017, 115: 567–578. doi: 10.1016/j.triboint.2017.07.009
- [25] Vasileiou, A., Denkena, B., Breidenstein, B., Topographical analysis of wear tracks on thin films using 3D areal parameters, *Wear*, 2020, 454–455: 203324. doi: 10.1016/j.wear.2020.203324
- [26] Sadeghi, A., Zhang, T., Komvopoulos, K., Wear mechanisms and durability of advanced PVD coatings under severe tribological loading, *Surf. Coat. Technol.*, 2021, 410: 126939. doi: 10.1016/j.surfcoat.2021.126939
- [27] Hawryluk, M., Gronostajski, Z., Widomski, P., Kaszuba, M.D., Ziemba, J., Smolik, J., Influence of the application of a PN + Cr/CrN hybrid layer on the improvement of the lifetime of hot forging tools, *J. Mater. Process. Technol.*, 2018, 258: 226–238
- [28] Hawryluk, M., Gronostajski, Z., Kaszuba, M.D., Polak, S., Widomski, P., Smolik, J., Analysis of the wear of forging tools surface layer after hybrid surface treatment, *Int. J. Mach. Tools Manufacture*, 2017, 114, 60–71
- [29] Nose, Y., Kawamoto, M., Funabashi, H., Formation and evolution of tribo-oxide layers on hard coatings at elevated temperatures, *Surf. Coat. Technol.*, 2018, 349, 1036–1045. doi: 10.1016/j.surfcoat.2018.06.078
- [30] Wojtaszek, M., Lisiecki, Ł., Łukaszek-Solek, A., Korpala, G., Zyguła, K., Śleboda, T., et al., Application of processing maps and numerical modelling for identification of parameters and limitations of hot forging process of 80MnSi8-6 steel, *Arch. Civ. Mech. Eng.*, 2023, 23: 240. doi: 10.1007/s43452-023-00783-8
- [31] Hawryluk, M., Dudkiewicz, Ł., Jabłońska, M., Polak, S., & Marzec, J., Analysis of the destruction of a die insert used in the industrial process of hot die forging to produce a yoke forging, *Eng. Fail. Anal.*, 2024, 164, 108661. doi: 10.1016/j.engfailanal.2024.108661
- [32] Chen, J., Wang, S., Li, Y., Zhang, G., Oxidative wear behavior of H13 steel under dry sliding conditions at elevated temperatures, *Tribology*, 2011, 31(4): 317–322
- [33] Cui, X., Wang, Z., Shen, B., Liu, J., Effect of tempering conditions on wear resistance in various wear mechanisms of H13 steel, *Tribol. Int.*, 2011, 44(7–8): 898–905. doi: 10.1016/j.triboint.2011.02.006
- [34] Wang, Y., Li, J., Zhang, H., Chen, Z., Impact of applied loads on wear mechanisms in H13 steel at various preheating temperatures during laser powder bed fusion additive manufacturing, *Wear*, 2024, 556–557: 205538. doi: 10.1016/j.wear.2024.205538