



Wear Mechanisms and Service Life of PVD-Coated Collar Dies in Coin Minting

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Abstract

Circulating coins remain indispensable in Thailand despite rapid digitalization, with the 5-baht denomination playing a critical role. Yet, collar dies used in its minting suffer frequent wear and premature failure, increasing production costs. This study systematically evaluated two cold-work tool steels – DIN 2379 (conventional) and Böhler K490 (powder metallurgy) – uncoated and coated with titanium nitride (TiN) or chromium nitride (CrN) via arc-PVD, under industrial high-speed minting. Testing included hardness and scratch adhesion, optical/SEM–EDS wear analysis, regression-based tool life prediction, quantitative coin quality assessment, and economic evaluation. Results demonstrated that substrate–coating synergy was decisive. TiN on DIN 2379 achieved the best overall performance, sustaining ~1.5 million coins with negligible defects, while uncoated DIN 2379 failed at ~0.67 million. CrN provided intermediate life (~0.95 million) but with lower adhesion stability. In contrast, K490 systems terminated early (~0.8–1.0 million coins) due to Cu–Ni debris accumulation, despite groove wear depths remaining below 4 µm. Regression models predicted >6 million coins for K490, but these values were invalid, highlighting the inadequacy of wear-only criteria. The novelty of this work lies in experimentally confirming, under industrial Thai minting conditions, that debris – not wear depth – governs die termination and product quality. TiN-coated DIN 2379 emerged as the most reliable and cost-effective option (~175,000 Baht per million coins), providing a framework for die management that integrates wear progression, debris effects, and economic efficiency.

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1. Introduction

Despite the global rise of digital payments, circulating coins remain indispensable in many economies. In Thailand, platforms such as PromptPay, mobile banking, and QR code transactions have transformed payment behavior. Yet, large segments of the population – particularly in rural areas and among low-income groups – still rely on cash due to limited access to digital infrastructure or financial literacy (Septeck, Socratyanurak, & Socratyanurak, 2023). Coins are critical for small-scale transactions, public transport, vending machines, and local markets, where digital alternatives are impractical. Thailand's informal economy also depends heavily on physical currency, with coins providing transactional flexibility (Chutipanich, 2025).

Globally, coins persist despite digitalization. The Royal Mint Annual Report (2021) confirmed that retail and service sectors continued using coins even during the COVID-19

pandemic. The U.S. Treasury (2022) similarly reported their necessity in small-scale commerce and among cash-dependent groups. Coins also ensure resilience during digital disruptions or cybersecurity incidents (Chucherd et al., 2018), while also serving as cultural and symbolic value through depictions of national heritage and monarchy.

Recent Thai statistics emphasize their continued significance. As of June 2025, the Bank of Thailand reported coins in circulation worth 89,906 million baht (Bank of Thailand, 2025). The 5-baht denomination is particularly important, with 224 million coins actively circulating (The Treasury Department Of Thailand, 2023). Although annual minting volumes are decreasing – from 1,070 million in 2024 to 900 million in 2025 (The Treasury Department of Thailand, 2025) Nevertheless, demand for the 5-baht coin remains robust.

The 5-baht coin is produced from a cupronickel-clad copper planchet (75 % Cu–25 % Ni outer layer, 99.5 % Cu core),



weighing 6 g and 24 mm in diameter, with a reeded edge of 78 serrations (Fig. 1 and 2). During minting, blanks are struck between upper and lower dies within a collar die, which forms the edge serrations (Fig. 3). The high-speed press (650–850 strokes/min) delivers rapid production, with regular quality checks monitoring for defects such as misaligned patterns, excessive rims, or collapsed edges. Among these, wearing collar die's reeded grooves is the most frequent cause of failure mode, resulting in defective coin edges (Fig. 4). At the Royal Thai Mint, uncoated hardened DIN 2379 collar dies typically last ~700,000 coins before replacement, thereby increasing production costs through frequent downtime.

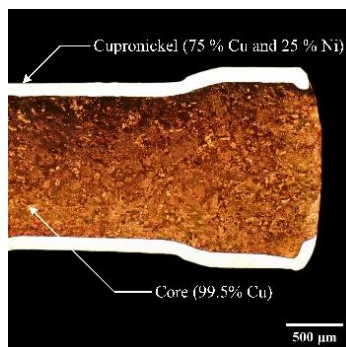


Fig. 1. Cross-section of the Thai 5-baht planchet showing cupronickel cladding and copper core



Fig. 2. The 5-baht coin issued since 2018: (a) obverse, (b) reverse, and (c) reeded edge

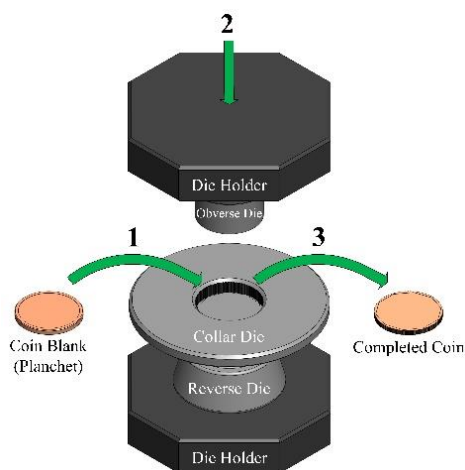


Fig. 3. Schematic sequence of the minting process for the 5-baht coin

Building on these industrial challenges, previous studies have investigated the mechanisms that limit collar die

performance in high-speed minting. Adhesive transfer from planchets, abrasive scratching from alloy inclusions, cyclic fatigue under repeated impact, and tribo-corrosion in humid conditions have consistently been identified as the dominant degradation modes (Cruz et al., 2022; Sutisna & Permana, 2022). The severity of these mechanisms depends strongly on substrate hardness, carbide distribution, coating integrity, and cleaning practices. Cupronickel alloys, such as those used in Thai 5-baht coins, exacerbate adhesive and abrasive wear due to their relatively high hardness and galling tendency (Fitruallah et al., 2015; Ithisoponakul, Wongsamarnmanee, & Premanond, 2014).

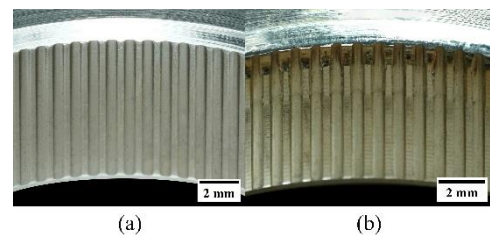


Fig. 4. Collar die used in 5-baht coin production: (a) new die, (b) worn die after ~700,000 coins

To counter these effects, hardened tool steels remain the standard for collar dies. DIN 2379 (AISI D2 equivalent) offers high wear resistance through its coarse carbide networks, though brittleness can lead to premature chipping. Böhler K490, produced by powder metallurgy, exhibits finer carbide dispersion that enhances toughness and dimensional stability. These microstructural distinctions explain their typical hardness levels (DIN 2379: 58–61 HRC; K490: 62–64 HRC) and justify their selection as substrates for this study (Elghazaly, 2023; Schlegel & Schneiders, 2024). Even with optimized substrates, however, service life remains limited without surface treatments such as physical vapor deposition (PVD) coatings (Ľavodová, Beňo, Monková, & Stančeková, 2023).

PVD coatings are widely recognized for their ability to enhance die durability by providing high hardness, strong adhesion, and low friction (Panjan, Drnovšek, Gselman, Čekada, & Panjan, 2020; Selvakumar & Barshilia, 2012). Two coatings are particularly relevant to coinage dies:

- Titanium Nitride (TiN): Hardness >2000 HV, friction coefficient 0.5–0.6, and excellent resistance to adhesive wear. TiN is widely used in forming tools and has shown consistent improvements in tool life (Gotman, Gutmanas, & Hunter, 2017; Krella, 2020; Xian et al., 2022).
- Chromium Nitride (CrN): Hardness 1500–2000 HV, friction coefficient 0.3–0.4, and superior corrosion resistance. CrN is often preferred where environmental humidity accelerates corrosion or adhesion (Adesina, Gasem, & Mohammed, 2019; Beliardouh, Bouzid, Nouveau, Tlili, & Walock, 2015; Cai, Huang, Yang, Wei, & Nagy, 2010).

Studies confirm that TiN and CrN coatings can extend die lifetimes toward one million coins while maintaining

dimensional stability and edge sharpness (Fernandes et al., 2017; Torsakul & Kuptasthien, 2024). Yet their long-term performance depends heavily on substrate properties, coating quality, and adhesion under cyclic impact, and systematic comparisons under industrial minting conditions remain scarce.

Importantly, the neglect of debris in prior studies persists because standard laboratory wear tests cannot replicate the cumulative debris buildup that occurs in high-speed industrial coinage, while production practice has historically relied on simple groove wear-depth thresholds (e.g., 20 μm) as the criterion for die replacement. As a result, debris-induced instability has not been systematically investigated, despite its clear influence on service life.

Although significant advances have been made in developing hard coatings and tool steels for forming applications, their performance in coin minting remains only partially understood. Prior work has shown that TiN and CrN coatings can increase hardness and reduce wear (Fernandes et al., 2017; Ľavodová et al., 2023; Torsakul & Kuptasthien, 2024), while substrate microstructure and tempering treatments influence tool life (Elghazaly, 2023; Schlegel & Schneiders, 2024). However, most investigations have evaluated these properties in isolation, without fully integrating them into a system-level framework that reflects industrial outcomes.

Four specific gaps emerge:

- Isolated property focus: Existing work emphasizes hardness, adhesion, or wear resistance individually, but seldom integrates them into a system-level framework connecting to die longevity and coin conformity (Fernandes et al., 2017; Sousa & Silva, 2020; Torsakul & Kuptasthien, 2024).
- Neglect of debris accumulation: The disruptive effect of Cu–Ni debris on high-speed striking has received little attention, even though emerging evidence suggests wear depth alone cannot explain early die termination (Smith, 2022; Trzepieciński, 2023). This gap persists because most laboratory wear tests cannot replicate industrial debris buildup, and production practice has relied on simple wear-depth thresholds.
- Limited linkage to product quality: Few studies have directly correlated die wear with quantitative quality metrics such as coin weight, edge pass rate, and defect frequency (Ľavodová et al., 2023).
- Overreliance on regression models: Conventional wear-based life predictions often ignore debris-induced failure, leading to systematic overestimation of usable service life (Jarfors, Castagne, Danno, & Zhang, 2017; Sousa & Silva, 2020).

This study addresses these gaps by integrating substrate–coating synergy, wear mechanisms, debris-induced instability, and coin quality outcomes into a single evaluation framework under industrial high-speed minting conditions. The contributions are fourfold:

- (i) Holistic framework: Hardness, scratch adhesion, wear progression, debris formation, and product conformity

are evaluated together, bridging material properties with industrial outcomes.

- (ii) Debris-limited failure mechanism: Results demonstrate that Cu–Ni debris accumulation, rather than groove wear depth alone, governs the effective service life of Böhler K490 dies, offering a new perspective on failure mechanisms in coin minting.
- (iii) Linkage to product quality: Die performance is quantitatively connected to coin conformity metrics (weight stability, edge pass rate, defect frequency), extending beyond traditional wear-only assessments.
- (iv) Realistic life prediction: Regression-based wear models are critically compared with observed early termination, clarifying why conventional approaches systematically overestimate die life.

By establishing TiN-coated DIN 2379 as the most reliable configuration for Thai 5-baht coin production – delivering both extended die life (~1.5 million coins) and defect-free outcomes – this study provides not only scientific insight but also practical guidance for cost reduction and operational efficiency in industrial minting.

2. Materials and Methods

2.1. Materials

Two cold-work tool steels were selected as collar die substrates: DIN 2379 (AISI D2 equivalent) and Böhler K490 Microclean. DIN 2379 is a conventionally produced high-carbon, high-chromium steel with coarse carbide networks, while K490 is a powder-metallurgy steel with refined carbide dispersion and improved toughness. Both were supplied in annealed condition as bar stock and manufactured into collar dies with a 23.80 mm inner diameter (Fig. 5) to match the 5-baht coin blank dimensions.

The manufacturing process involved:

- Blank preparation and rough machining: Blanks were saw-cut, rough turned and bored on a CNC lathe (Quick Turn Nexus 250-II MSY, Mazak, Japan), leaving a grind allowance. Datum and locating features ensured repeatable fixture.
- Stress relief: Conducted at 600°C for 2 h in air, followed by inspection to confirm dimensional stability.
- Finishing: Cylindrical and face grinding were performed to tolerance; surface roughness prior to coating was $R_a \leq 0.10 \mu\text{m}$. Reeded grooves (78 serrations) were produced using wire-EDM (MV1200R, Mitsubishi, Japan) with rotary indexing, then hand-polished to $R_a \leq 0.05 \mu\text{m}$.
- Pre-coating preparation: Non-functional surfaces were masked, dies were demagnetized, and cleaned via alkaline wash, ultrasonic acetone and ethanol, and filtered air drying. Optical inspection and dimensional checks confirmed conformity.
- Traceability: Each die was laser-marked (Pulsaris 300, Lang, Germany) with substrate type, heat-treatment batch, and inspection ID.

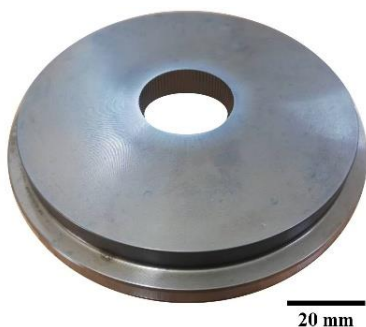


Fig. 5. Collar die shown in inverted position prior to surface treatment

The chemical compositions are shown in Table 1.

Table 1. Chemical composition of DIN 2379 and Böhler K490 steels (wt%).

Materials	C	Si	Mn	Cr	Mo	V	W
DIN 2379	1.50	0.10	0.15	11.50	0.60	0.90	-
Böhler K490	1.40	-	-	8.00	2.00	3.7	3.5

The coin blanks (planchets) were standard Thai 5-baht cupronickel-clad copper, consisting of outer layers of 75 % Cu – 25 % Ni bonded to a 99.5 % Cu core. Each weighed 6.0 g, measured 24 mm in diameter, and featured 78 serrations in accordance with Treasury Department specifications. Representative planchets used in the trials are shown in

Fig. 6.



Fig. 6. Cupronickel-clad copper planchets prepared for minting trials

2.2. Heat Treatment

Heat treatment was carried out in a vacuum furnace (IVA Schmetz, Germany) with nitrogen atmosphere and gas quenching. The parameters are summarized in Table 2. The treatments were designed to achieve ~60 HRC for DIN 2379 and ~63 HRC for K490, with measured hardness values reported in Section 3.

2.3. Coating Deposition

The hardened dies were coated with TiN and CrN using an arc-PVD system (MZR-303, Sulzer Metaplas Ionon, Germany). Prior to deposition, surfaces were polished to $R_a \leq 0.05 \mu\text{m}$ and ultrasonically cleaned. The deposition parameters are summarized in Table 3. Coating thicknesses were later confirmed by SEM cross-sections and are reported in Section 3.

Table 2. Heat treatment parameters for DIN 2379 and Böhler K490

Materials	Hardening	Quenching	Tempering cycles
DIN 2379	1,020°C – 30 min	N ₂ , 6 bar	540°C – 2 h × 3
Böhler K490	1,050°C – 30 min	N ₂ , 6 bar	530°C – 2 h; 550°C – 2 h × 2

Table 3. Arc-PVD deposition parameters for TiN and CrN coatings

Process parameters	Quantities
Arc current	75 A
Coating temperature	400–450°C
Nitrogen flow rate	500 cm ³ /min
Argon flow rate	300 cm ³ /min
Coating duration	5–6 h

2.4. Minting Trials

Minting experiments were conducted at the Royal Thai Mint using a Grabener MPU 156 high-speed press.

- Operating conditions: Press force 400–450 kN, stroke rate 650 strokes/min.
- Die configuration: Upper and lower dies produced the obverse and reverse images, while the collar die formed the reeded edge.
- Batch size: Each substrate–coating condition was tested with five collar dies.

Failure criteria were defined as follows:

- Reeded groove wear exceeding the Treasury Department specification, set at a maximum allowable wear depth of 20 μm .
- Visible chipping or cracking the collar die.
- Production of coins outside the official weight tolerance ($\pm 0.15 \text{ g}$).

A wear depth of 20 μm was adopted as the operational failure threshold, corresponding to the official replacement limit used by the Royal Thai Mint based on decades of historical die performance. This criterion aligns with broader practices in coining and forming-tool studies, where maximum allowable wear depths are established to preserve relief fidelity and product conformity (Fernandes et al., 2017; Ithisoponakul et al., 2014; Ľavodová et al., 2023). Simulation-assisted studies have likewise confirmed that excessive wear directly compromises coin relief and dimensional accuracy, supporting wear-based replacement thresholds (Navarrete et al., 2020).

Importantly, our experimental observations also confirmed that once groove wear exceeded ~20 μm , reeded-edge defects and dimensional drift became visible in minted coins. Thus, this threshold is not only institutionally defined but also technically validated by product-quality outcomes, making it an appropriate and practical criterion for die life assessment in this study.

The wear depth was determined as the vertical distance between the unworn reference profile and the worn groove crest, observed using an optical microscope (BH-2, Olympus, Japan) at 1000 $\times$ magnification, as illustrated in Fig. 7. This 20 μm maximum depth was applied as the die-replacement threshold in the present study.

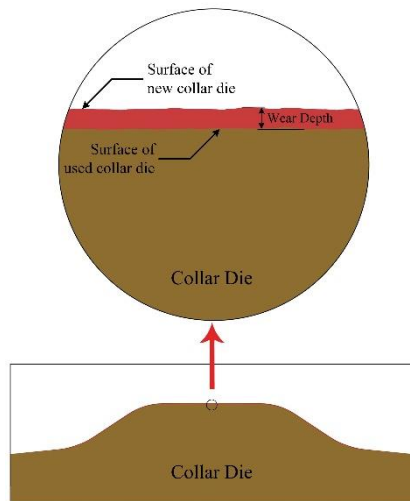


Fig. 7 Measurement of groove wear depth using optical microscopy

2.5. Characterization and Testing

2.5.1 Microstructural Analysis

Microstructural features of the substrates and worn dies were examined using:

- Optical microscopy (OM): Olympus BH-2 microscope, samples etched with 4 % Nital. Magnifications up to 1000× were employed to observe carbide morphology and reeded-groove wear depth.
- Scanning electron microscopy (SEM): Hitachi SU3500 operated at 15 kV for higher-resolution analysis of coating morphology, worn surfaces, and wear debris.
- Energy-dispersive X-ray spectroscopy (EDS): EX370 E-MAX detector used to identify elemental transfer (e.g., Cu/Ni from planchets) and debris composition. Particular attention was given to collar-groove debris mapping, where localized Cu–Ni transfer and coating fragments (Ti, Cr) were quantified. Representative results from this analysis are presented in Fig. 13–Fig. 15, demonstrating the mechanism of debris accumulation that governed Böhler K490 performance.

2.5.2. Hardness and Adhesion Tests

- Substrate hardness: Verified on a Rockwell C tester (HR-530, Mitutoyo, Japan).
- Coating microhardness: Measured with Innovatest Nexus 8000 microhardness tester at HV0.025 (25 gf, 10 s dwell). Ten indents per coating were averaged.
- Scratch adhesion test: Conducted on an Anton Paar Revetest scratch tester with progressive load from 1–200 N. The upper limit of 200 N was selected in accordance with ASTM C1624 guidelines and prior studies on arc-PVD TiN and CrN coatings on tool steels, where critical spallation typically occurs well below this threshold (Manasijevic et al., 2019; Shalaby et al., 2014). This limit ensured that catastrophic coating delamination could be reliably induced without risking excessive substrate damage. Acoustic emission and friction force were continuously recorded, and three scratches were

performed per sample. The critical load (L_c) for coating failure was identified by acoustic emission spikes, sudden frictional jumps, and post-test optical/SEM inspection. In practice, both TiN and CrN coatings exhibited coating failure within this load range, confirming the adequacy of the 200 N maximum.

2.5.3. Wear Rate Determination

Reeded groove wear was measured at 100,000-coin intervals. Optical micrographs at 1000× magnification were captured, and groove profiles were analyzed using ImageJ software (NIH, USA). Wear depth was defined as the vertical distance between the unworn reference profile and the worn groove crest, and wear rates ($\mu\text{m}/\text{coin}$) were obtained from linear regression of wear depth against production volume.

2.5.4. Coin Quality Evaluation

At each 100,000-coin interval, 30 coins were sampled for quality assessment:

- Weight: Measured using a Sartorius T1922/LC6200S precision balance (± 0.001 g).
- Edge quality: Inspected with OM at 45× magnification to detect rounding, collapse, or flash formation.
- Surface condition: Examined by SEM to detect material transfer, pitting, or surface tearing.

Coins outside the Treasury Department's tolerance limits (± 0.15 g weight deviation or unacceptable edge defects) were classified as defective.

2.6. Economic Evaluation Method

Die procurement costs were obtained from supplier records (Table 4). Effective die life values were taken from the observed outcomes reported in Section 3.4. Production losses during die changeovers were calculated based on press output (650 coins/min) and setup duration (1.333 h per replacement). The lost coins per setup were multiplied by the nominal coin value (5 Baht) to quantify downtime losses. It needs to be noted that downtime cost was expressed solely in terms of lost coin value; labor and energy costs were excluded to align with the Royal Thai Mint's accounting framework.

Table 4. Collar die procurement costs used in economic evaluation

Material	Cost (Baht/die)
Uncoated DIN 2379	1100
TiN on DIN 2379	1500
CrN on DIN 2379	1500
TiN on Böhler K490	4700
CrN on Böhler K490	4700

For each die system, the total cost per one million coins was calculated as:

- die cost normalized to effective life, plus
- downtime losses normalized to effective life.

Results are presented in Section 3.6 as cost per 10^6 coins (Baht), enabling direct comparison of economic efficiency across substrate–coating systems.

2.7. Experimental Design and Data Analysis

The study compared four substrate–coating combinations:

- (i) DIN 2379 + TiN
- (ii) DIN 2379 + CrN
- (iii) Böhler K490 + TiN
- (iv) Böhler K490 + CrN

For each condition, five collar dies ($n = 5$) were tested to ensure statistical reliability. Die life was recorded as the number of coins produced before failure, according to the criteria defined in Section 2.4.

Data were processed as follows:

- Wear progression: Wear depth measurements at 100,000-coin intervals were fitted using linear regression to estimate wear rates ($\mu\text{m}/\text{coin}$).
- Hardness and adhesion tests: Results were reported as mean $\pm$ standard deviation (SD).
- Statistical comparisons: One-way ANOVA was used to assess differences among die–coating groups, with significance set at $p < 0.05$. Where applicable, Tukey's post-hoc test was applied to identify pairwise differences.
- Confidence intervals: For all outcomes aggregated at the die level ($n = 5$ per condition), results are reported as mean $\pm$ SD together with two-sided 95% confidence intervals.
- Software: All analyses were performed using Minitab 18 (Minitab LLC, USA).

3. Results and discussion

3.1. Hardness of Substrates and Coatings

The hardness values of the heat-treated substrates and the microhardness of the TiN and CrN coatings are summarized in Table 5. DIN 2379 achieved an average hardness of 59.2 ± 0.6 HRC, while Böhler K490 reached 62.4 ± 0.5 HRC. These results are consistent with reported ranges for cold-work tool steels subjected to optimized tempering, where conventionally produced DIN 2379 typically attains 58–61 HRC, while powder-metallurgy steels such as K490 reach 62–64 HRC due to their refined microstructure (Elghazaly, 2023; Schlegel & Schneiders, 2024).

Table 5. Hardness of substrates and coatings (mean $\pm$ SD, 95% CI)

Material/Coating	Hardness (mean $\pm$ SD)	95% CI (Hardness)
DIN 2379 substrate	59.2 ± 0.6 HRC	[58.46, 59.94] HRC
Böhler K490 substrate	62.4 ± 0.5 HRC	[61.78, 63.02] HRC
TiN coating	2300 ± 85 HV0.025	[2194.5, 2405.5] HV0.025
CrN coating	1650 ± 70 HV0.025	[1563.1, 1736.9] HV0.025

The microstructures in Fig. 8 provide direct evidence for these hardness differences. DIN 2379 displayed coarse carbide networks typical of conventionally produced high-carbon, high-chromium steels, which contribute to moderate

hardness but reduced toughness. In contrast, Böhler K490 exhibited a fine, uniform dispersion of carbides associated with powder-metallurgy steels, explaining its slightly higher hardness (~ 3 HRC) and improved dimensional stability.

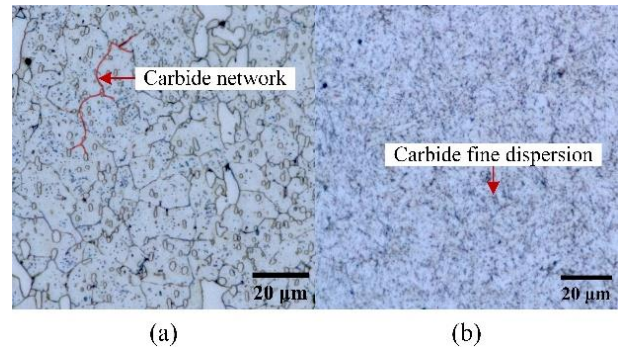


Fig. 8. Microstructures of hardened substrates: (a) DIN 2379 with carbide networks, (b) Böhler K490 with fine carbides

The coatings exhibited hardness values significantly higher than the substrates. TiN measured $2,300 \pm 85$ HV0.025, whereas CrN averaged $1,650 \pm 70$ HV0.025. These results are in agreement with reported ranges for arc-PVD coatings, where TiN typically falls between 2,200–2,500 HV and CrN between 1,500–1,800 HV (Manasijevic et al., 2019; Shalaby et al., 2014). The indentation load of 25 gf restricted penetration depth to the coating layer, minimizing substrate influence in accordance with ASTM E384. The relatively narrow scatter ($<5\%$ of the mean) indicates uniform coating quality and consistent deposition. Similar microhardness profiles were also confirmed by Sousa & Silva (2020) in nanolayer CrN/TiAlN systems, underscoring that optimized arc-PVD deposition can consistently produce high-performance nitride coatings for forming dies.

The modest hardness difference between DIN 2379 and K490 (~ 3 HRC) nevertheless reflects a fundamental microstructural distinction between conventionally processed and PM steels. Similarly, the larger difference in coating hardness highlights the contrasting roles of TiN and CrN: TiN offers superior resistance to abrasive wear due to its higher hardness, while CrN, though softer, is valued for its improved toughness and thermal stability. These results establish the baseline for interpreting adhesion, wear mechanisms, and die life in the subsequent sections.

3.2. Coating Thickness and Adhesion

The thickness of the TiN and CrN coatings deposited on the collar dies was measured from cross-sectional SEM images. Representative micrographs are shown in Fig. 9, and average thickness values are summarized in Table 6. TiN exhibited a mean thickness of 3.1 ± 0.2 μm , while CrN averaged 2.8 ± 0.2 μm . Both coatings showed good uniformity across the functional surfaces, with variations remaining within $\pm 8\%$ of the mean. These values are consistent with typical ranges reported for arc-PVD nitride coatings used in tooling applications, where TiN thicknesses of 2.5–3.5 μm and CrN thicknesses of 2.5–3.0 μm are common (Manasijevic et al., 2019; Shalaby et al., 2014; Sousa & Silva, 2020).

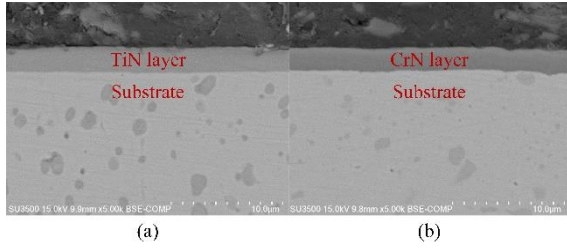


Fig. 9. SEM cross-sections of coatings: (a) TiN, (b) CrN

Table 6. Thickness of TiN and CrN coatings (mean $\pm$ SD, 95% CI)

Materials	Thickness (mean $\pm$ SD)	95% CI (Thickness) (μm)
TiN	$3.10 \pm 0.2 \mu\text{m}$	[2.852, 3.348]
CrN	$2.80 \pm 0.2 \mu\text{m}$	[2.552, 3.048]

Coating adhesion strength was evaluated using a modular scratch tester (RTS 100, Anton Paar, Austria) equipped with a diamond stylus. A progressive load from 1–200 N was applied until coating rupture and detachment occurred, yielding critical loads for crack initiation (L_{c1}), progressive delamination (L_{c2}), and complete coating failure (L_{c3}), in accordance with ASTM C1624. The 200 N maximum load was selected based on ASTM standards and prior PVD coating studies (Manasijevic et al., 2019; Shalaby et al., 2014), ensuring that catastrophic coating failure could be induced without excessive substrate damage. In practice, all coatings exhibited failure within this range, confirming the adequacy of the selected test parameters.

For DIN 2379, TiN coatings achieved mean critical loads of 15.47 N (L_{c1}), 69.99 N (L_{c2}), and 124.01 N (L_{c3}). These results indicate strong adhesion, particularly resistance to catastrophic coating loss. CrN on DIN 2379 showed higher resistance to initial cracking (L_{c1} = 19.04 N) but lower values for progressive and complete failure (L_{c2} = 56.44 N, L_{c3} = 104.76 N) (Fig. 10). These findings are supported by prior work demonstrating TiN's superior adhesion and fracture resistance under cyclic high-loads (Fernandes et al., 2017; Smith, 2022; Sousa & Silva, 2020).

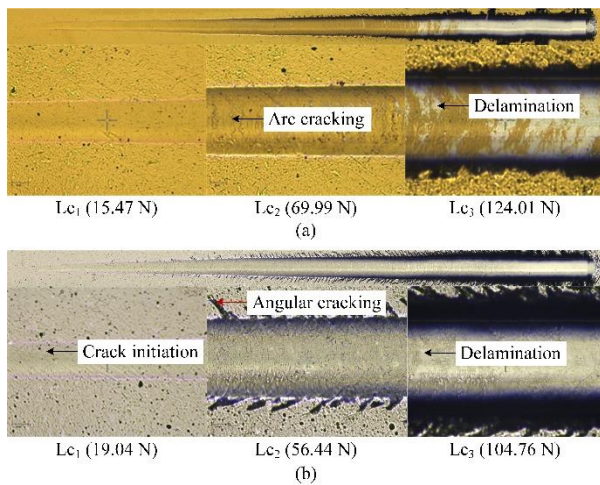


Fig. 10. Scratch test results for DIN 2379: (a) TiN, (b) CrN

For Böhler K490, TiN coatings yielded 19.47 N (L_{c1}), 58.77 N (L_{c2}), and 113.35 N (L_{c3}), suggesting greater resistance to crack initiation but slightly lower resistance to progressive delamination compared with TiN on DIN 2379. CrN on K490 recorded the lowest L_{c1} (16.55 N), pointing to susceptibility to early micro-cracks, but achieved moderate L_{c2} (66.65 N) and L_{c3} (105.02 N) values (Fig. 11).

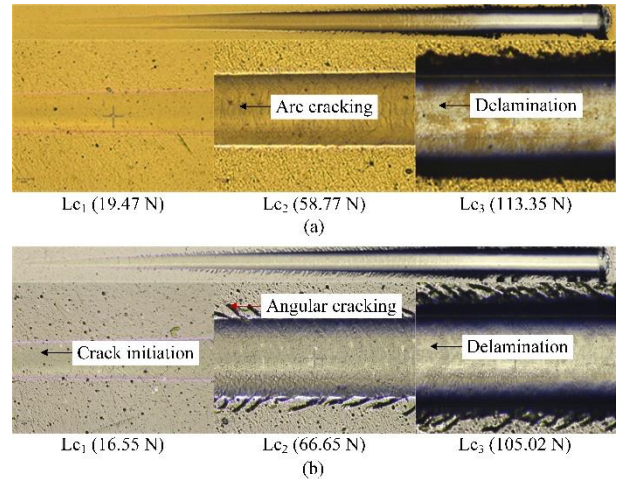


Fig. 11. Scratch test results for Böhler K490: (a) TiN, (b) CrN

Representative scratch tracks are presented in Fig. 10–Fig. 11, with arrows marking cracks and delamination. As shown in Fig. 12 and Table 7, TiN provided significantly higher L_{c3} values than CrN across both substrates, while CrN exhibited slightly higher L_{c1} values, indicating delayed crack initiation but earlier catastrophic failure.

Overall, TiN consistently demonstrated greater resistance to complete coating failure (L_{c3}) across both substrates, confirming its superior durability under cyclic, high-frequency minting conditions. CrN generally showed higher resistance to initial cracking (L_{c1}), particularly on DIN 2379, delaying micro-crack initiation. However, its lower L_{c2} and L_{c3} values indicated earlier delamination and catastrophic failure. These findings are consistent with Fernandes et al. (2017), who linked TiN's higher hardness and adhesion to superior resistance under progressive loading. Ľavodová et al. (2023) emphasized that catastrophic failure (L_{c3}) governs die service intervals more critically than early cracking, while Torsakul and Kuptasthien (2024) confirmed that PVD TiN coatings exhibit superior adhesion under repeated high-load contact. Sousa & Silva (2020) further reinforced that nanostructured TiN architectures demonstrate more stable failure progression than CrN under complex tool–workpiece interaction regimes.

While scratch L_c values are a standard proxy for adhesion, they probe quasi-monotonic damage under steadily increasing load. High-frequency minting imposes cyclic impact and high shear rates, where coating–substrate compliance matching and energy-dissipation pathways become decisive; coatings that appear comparable in scratch tests can diverge markedly in impact-fatigue and third-body generation during production (Manasijevic et al., 2019; Shalaby et al., 2014; Sousa & Silva, 2020).

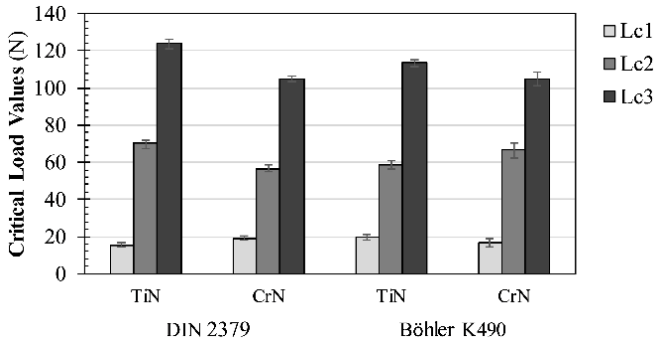


Fig. 12. Comparison of critical loads (Lc₁–Lc₃) for TiN and CrN coatings on DIN 2379 and Böhler K490

Table 7. Critical loads (Lc₁–Lc₃) from scratch tests on TiN- and CrN-coated dies

Material/Coating	Lc1 (N)	Lc2 (N)	Lc3 (N)
TiN on DIN 2379	15.47 ± 1.10 [14.10–16.84]	69.99 ± 1.50 [68.07–71.91]	124.01 ± 1.60 [122.07–125.95]
CrN on DIN 2379	19.04 ± 1.08 [17.70–20.38]	56.44 ± 1.45 [54.57–58.31]	104.76 ± 0.90 [103.73–105.79]
TiN on Böhler K490	19.47 ± 1.00 [18.23–20.71]	58.77 ± 1.40 [56.94–60.60]	113.35 ± 0.85 [112.29–114.41]
CrN on Böhler K490	16.55 ± 1.20 [15.06–18.04]	66.65 ± 1.90 [64.44–68.86]	105.02 ± 2.10 [102.58–107.46]

3.3. Wear Mechanisms of Collar Dies

Representative optical micrographs of groove wear progression are shown in Fig. 13. After 0.5 M coins, early rounding of groove crests was observed. At 1.0 M coins, more pronounced flattening occurred, with arrows indicating measurable wear depth relative to the unworn reference. By 1.5 M coins, significant crest degradation was evident, marking the approach to the 20 μm failure threshold. These observations provide direct visual confirmation of progressive groove wear during high-speed minting.

SEM analysis of worn groove surfaces (Fig. 14) revealed two dominant wear modes: (a) abrasive scratches aligned along the groove crests, and (b) adhesive Cu–Ni transfer films adhered to coating surfaces. Arrows in Fig. 14 highlight both abrasion and adhesion as key contributors to coating deterioration during high-frequency stamping.

For TiN, wear was dominated by fine abrasive scratches with limited adhesive transfer, indicating strong resistance to delamination. In contrast, CrN exhibited more pronounced adhesive transfer layers, which served as initiation sites for coating delamination and accelerated groove wear. Such observations align with previous reports that identified adhesive material transfer as a critical factor in the failure of PVD coatings under cyclic loading (Fernandes et al., 2017; Ľavodová et al., 2023). Trzepieciński (2023) further documented that transfer films composed of Cu-based planchet alloys create localized bonding zones that promote interfacial instability and micro-delamination, especially in softer coatings like CrN. In addition to these microscale wear features, macroscopic debris formation was observed during high-speed minting with Böhler K490 dies.

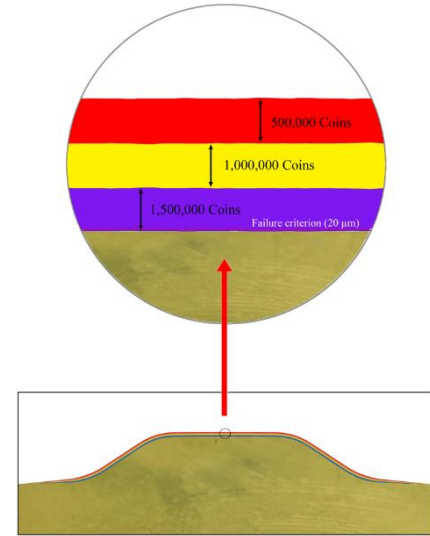


Fig. 13. Optical micrographs of reeded groove wear after 0.5M, 1.0M, and 1.5M coin production

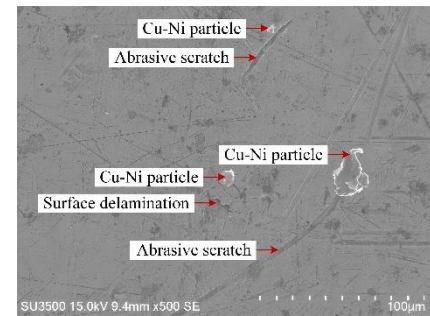


Fig. 14. SEM images of worn grooves showing (a) abrasive scratches, (b) adhesive Cu–Ni transfer layer

As shown in Fig. 15, large Cu–Ni flakes accumulated around the collar die, while optical microscopy of collected debris revealed irregular lamellar morphologies up to 100 μm in size. This debris originated from adhesive transfer and delamination at the die–planchet interface. Its accumulation disrupted machine stability and led to premature test termination, even though the 20 μm wear threshold was never reached. These findings confirm that debris formation is a dominant wear mechanism in K490 systems, governing effective die life independently of groove wear depth. This aligns with Smith (2022), who emphasized that metal-on-metal contact debris, particularly from Cu-based planchets, creates mechanical build-up and machine vibration, eventually outweighing the importance of wear progression in tool failure scenarios.

Previous investigations into PVD-coated dies have primarily emphasized hardness, adhesion strength, or groove wear depth as the dominant factors influencing service life (Fernandes et al., 2017; Ľavodová et al., 2023; Torsakul & Kuptasthien, 2024). While these metrics remain important, our findings provide the first experimental demonstration under industrial Thai coin minting conditions that Cu–Ni debris accumulation – not groove wear – governs premature termination of collar dies. This is particularly evident in

Böhler K490 systems, where dies failed at shallow wear depths ($<4 \mu\text{m}$), far earlier than regression wear models predicted ($>6 \text{ M}$ coins). Such divergence highlights the inadequacy of wear-only approaches in predicting die life, revealing that debris-induced instability is the critical failure mechanism. By directly linking debris formation with both die survival and coin quality outcomes, this study establishes a system-level framework absent in earlier coating and tooling research.

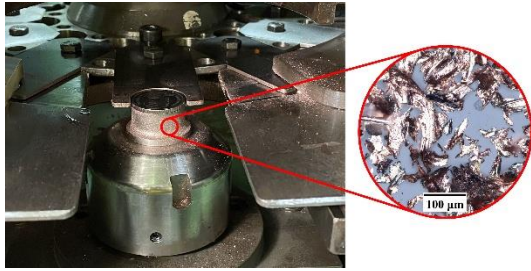


Fig. 15. Wear debris accumulation: (a) macroscopic debris in the press, (b) optical micrograph of Cu–Ni flakes ($\sim 100 \mu\text{m}$)

To verify the chemical origin of the debris, EDS analysis was performed on debris flakes and compared with the Cu–Ni planchet alloy. The spectra (Fig. 16) confirmed that debris consisted almost exclusively of Cu and Ni, with minor C and O, consistent with surface oxidation during high-speed coining. Importantly, no significant Fe, Cr, Mo, or W peaks were detected, confirming that the debris did not originate from the die material but from adhesive transfer of the planchet alloy.

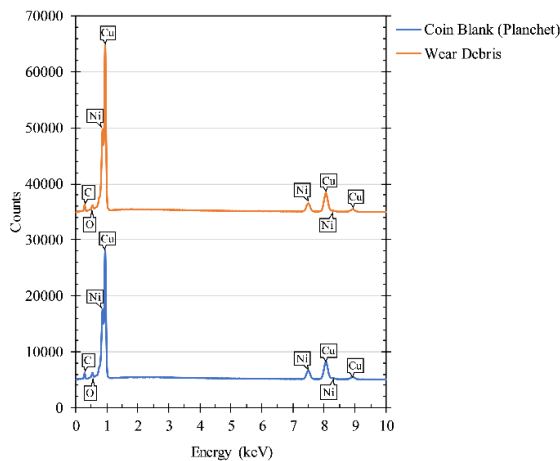


Fig. 16. EDS spectra of planchet and debris, confirming Cu–Ni composition

The quantitative EDS results (Table 8) further support this conclusion. Planchet composition was measured as $\sim 70 \text{ wt}\%$ Cu and $21 \text{ wt}\%$ Ni. Debris samples showed a similar composition, with Cu enrichment up to $90 \text{ wt}\%$ in some flakes due to preferential transfer of Cu during adhesive delamination. The variation in Ni content ($0.53\text{--}17.7 \text{ wt}\%$) indicates selective flake detachment, but the overall composition remained consistent with the planchet alloy.

Table 8. EDS composition of planchet alloy and collected wear debris

Sample	Element (wt%)							Total
	C	O	Mg	Al	Si	Ni	Cu	
Planchet	7.77	1.53	-	-	-	21.15	69.55	100
Debris 1	7.68	1.08	-	-	-	17.74	73.51	
Debris 2	8.69	2.00	0.21	0.12	0.20	3.86	84.91	100
Debris 3	7.67	1.79	-	-	-	0.53	90.00	

3.4. Die Life Comparison

The service life of collar dies was evaluated using both regression-based predictions and experimental outcomes. Table 9 summarizes regression equations, coefficients of determination (R^2), and predicted lifetimes at the $20 \mu\text{m}$ wear threshold, while Fig. 17 shows the fitted curves. Across all conditions, regression models exhibited strong linear fits ($R^2 > 0.95$), confirming consistent wear progression with production volume. Such regression-based approaches, where groove wear depth is treated as the primary failure criterion, have been widely used in tool life modeling for forming dies (Jarfors et al., 2017; Sousa & Silva, 2020). Predicted lifetimes in this study ranged from $\sim 0.67 \text{ M}$ coins for uncoated DIN 2379 to $\sim 1.5 \text{ M}$ coins for TiN-coated DIN 2379, consistent with prior findings that PVD TiN coatings extend service life in tooling and minting applications (Fernandes et al., 2017; Ľavodová et al., 2023; Torsakul & Kuptasthien, 2024).

For Böhler K490, regression curves extrapolated to the $20 \mu\text{m}$ wear criterion yielded apparent lifetimes exceeding $5\text{--}6 \text{ M}$ coins. However, these predictions were invalid: both TiN- and CrN-coated K490 dies were withdrawn after only $\sim 0.8\text{--}1.0 \text{ M}$ coins due to excessive Cu–Ni debris accumulation, despite groove wear depths remaining below $4 \mu\text{m}$ (Table 10; Fig. 18). The high extrapolated values reflect curve-fitting artifacts arising from the assumption of monotonic wear progression. This underscores the limitation of regression-based models when secondary mechanisms govern failure.

Table 9. Regression equations, R^2 values, and predicted die life based on wear depth

Materials	Regression equation (y in μm , x in coins)	R^2	Predicted die life ($\times 10^6$ coins)
Uncoated DIN 2379	$y = 2.971 \cdot 10^{-5}x + 0.028$	0.999	0.673
TiN on DIN 2379	$y = 1.146 \cdot 10^{-11}x^2 - 4.051 \cdot 10^{-6}x + 0.470$	0.999	1.494
CrN on DIN 2379	$y = 1.398 \cdot 10^{-11}x^2 + 8.136 \cdot 10^{-6}x - 0.486$	0.996	0.954
TiN on Böhler K490	$y = 3.087 \cdot 10^{-6}x + 0.008$	0.980	6.664*
CrN on Böhler K490	$y = 3.260 \cdot 10^{-6}x + 0.071$	0.984	6.643*

* Extrapolated beyond observed range; not representative of effective die life.

Note: predicted values are model outputs and do not include SD or CI.

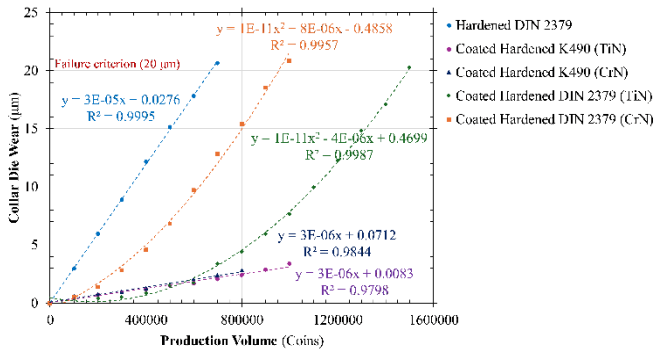


Fig. 17. Regression curves of groove wear depth versus production volume with 20 µm threshold

Comparisons with published datasets reinforce these outcomes. For DIN 2379, the effective lifetimes (~0.67 M uncoated, ~0.95 M CrN-coated, and ~1.5 M TiN-coated) align with Fernandes et al. (2017), who reported a twofold increase in coated tool life in stamping, and with Ľavodová et al. (2023), who demonstrated service life improvements in coinage dies via PVD. CrN's intermediate durability also corresponds with Adesina et al. (2019), who documented lower adhesion margins for CrN compared with TiN. These consistencies confirm the robustness of DIN 2379 systems. In contrast, the premature termination of K490 diverges from expectations in cold forming, where PM steels typically outperform conventional grades (Elghazaly, 2023; Jarfors et al., 2017). This discrepancy highlights the unique role of debris accumulation in high-speed coinage, consistent with tribological studies emphasizing debris-limited failure (Smith, 2022; Trzepieciński, 2023). Similar challenges have also been noted in simulation-assisted coining (Navarrete et al., 2020) and in forming processes where particle buildup accelerated tool degradation (Ithisoponakul et al., 2014; Sousa & Silva, 2020).

The premature termination of K490 systems can be attributed to their refined carbide distribution, which creates numerous micro-asperities at the die–planchet interface.

Table 10. Coin weight conformity for different die systems (mean ± SD, 95% CI)

Materials	Effective die life (coins)	95% CI (Effective die life) (coins)
Uncoated DIN 2379	672,506 ± 1,708 ¹	[670,385 – 674,627]
TiN on DIN 2379	1,494,314 ± 1,386 ¹	[1,492,594 – 1,496,035]
CrN on DIN 2379	954,052 ± 1,030 ¹	[952,773 – 955,331]
TiN on Böhler K490	985,434 ± 9,102 ²	[974,134 – 996,734]
CrN on Böhler K490	806,408 ± 8,220 ²	[796,203 – 816,612]

¹ Failure criterion: Wear depth ≥ 20 µm.

² Failure criterion: Terminated due to debris.

Note: no catastrophic fracture occurred; Böhler K490 dies were debris-limited.

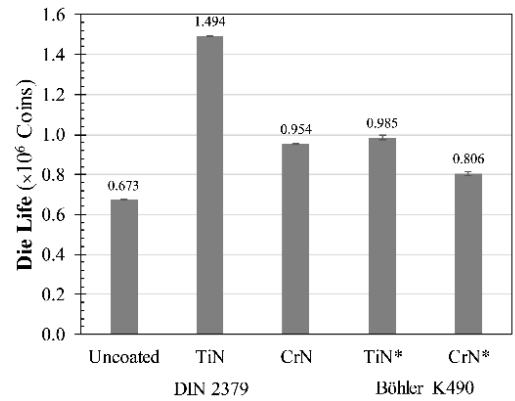


Fig. 18. Observed effective die life of collar dies with 95% confidence intervals

Under cyclic high-frequency impact, these asperities increase local stresses, promoting micro-chipping, Cu–Ni adhesion, and third-body formation.

Direct evidence is provided in Figs. 13–15, where SEM/EDS analyses revealed Cu–Ni-rich debris clusters compacted in grooves along with Ti or Cr fragments from spalled coatings. These micrographs illustrate a pickup → agglomeration → debris bed pathway that destabilized K490 dies before the 20 µm wear threshold was reached. Two mechanisms amplify this cycle: (i) higher contact stiffness in K490 accelerates planchet pickup, and (ii) coating–substrate mismatch exacerbates debris, with CrN prone to micro-spallation and TiN shedding fragments under elastic–plastic shakedown. This adhesion-driven instability is consistent with unstable tool–planchet interactions described by Smith (2022), and with the hierarchy of adhesion performance (TiN > CrN) reported in PVD studies (Jarfors et al., 2017).

This mechanistic interpretation also aligns with Trzepieciński (2023), who emphasized that secondary mechanisms such as debris entrapment and surface instability can dominate over classical wear progression in high-frequency forming. The divergence between predicted lifetimes (wear-limited, Table 9/Fig. 17) and observed outcomes (debris-limited, Table 10/Fig. 18) highlights the inadequacy of regression-only approaches. Importantly, no catastrophic fracture was observed, confirming that die replacement was operational rather than structural.

Statistical analysis reinforced these findings. One-way ANOVA ($F(4,20) = 19,190.86$, $p < 0.0001$) showed highly significant differences among groups. Tukey's post-hoc test revealed that TiN on DIN 2379 lasted significantly longer than all other conditions ($p < 0.05$). CrN on DIN 2379 was also superior to the uncoated substrate but inferior to TiN. No significant difference was observed between TiN- and CrN-coated K490, reflecting their common limitation by debris accumulation.

From an industrial perspective, these results demonstrate that while DIN 2379 die life can be predicted reliably by wear progression, K490 requires debris-mitigation strategies such as groove finishing, multilayer or gradient coatings, or preventive cleaning intervals. More broadly, the findings emphasize the need for system-level frameworks that integrate

substrate–coating synergy, wear progression, debris formation, and product conformity into die performance assessment (Ithisoponakul et al., 2014; Sousa & Silva, 2020).

Although Böhler K490 (PM) is harder and nominally superior to DIN 2379, three stack-level effects rationalize its higher Cu–Ni pickup and earlier debris-induced termination. First, die–planchet contact mechanics: at a given normal load, a stiffer, less plastically accommodating substrate concentrates shear at asperity summits. Adhesive micro-junctions therefore nucleate and detach more readily, forming transfer films and loose flakes—an established pathway in adhesive wear of rough metallic contacts (Smith, 2022; Trzepieciński, 2023). Second, coating–substrate compliance mismatch under high-frequency impact: scratch critical loads (quasi-monotonic) do not fully predict behavior in cyclic impact. Under minting, a stiffer substrate can shift cyclic shear into the coating and interface, promoting micro-spallation and third-body formation even when L_c values are similar (Manasijevic et al., 2019; Shalaby et al., 2014). Multilayer/graded nitride architectures are known to mitigate this by smoothing modulus transitions and improving impact-fatigue tolerance (Sousa & Silva, 2020). Third, micro-topography and carbide-scale effects: the refined, uniformly dispersed carbides in PM steels can leave a dense field of sharp micro-asperities after finishing, elevating real-contact stress and favoring junction growth with Cu–Ni planchets that are inherently prone to galling/transfer (Ithisoponakul et al., 2014; Trzepieciński, 2023). Collectively, these effects produce a junction growth → transfer film → third-body bed loop that destabilizes K490 stacks at shallow geometric wear, explaining the divergence between regression life (wear-depth based) and observed early termination (Smith, 2022; Trzepieciński, 2023). Practically, the results point to mitigation via (i) multilayer/graded coatings (e.g., CrN/TiAlN variants), (ii) finer, low-energy surface finishes to blunt asperities, and (iii) scheduled debris-clearing intervals, rather than reliance on wear-depth thresholds alone (Sousa & Silva, 2020).

3.5. Coin Quality Outcomes

While die life provides a critical measure of tooling performance, product conformity ultimately determines whether a die can remain in service. Quality was therefore evaluated in terms of coin weight stability and edge defect rates.

3.5.1. Coin Quality Outcomes

While die life provides a critical measure of tooling performance, product conformity ultimately determines whether a die can remain in service. Quality was therefore evaluated in terms of coin weight stability and edge defect rates. In contrast, Böhler K490 dies produced lighter coins (5.790–5.792 g) and generated measurable populations of out-of-spec weights (2,500–3,200 pieces). These deviations indicate that debris accumulation and premature instability, rather than groove wear, disrupted weight control. Such outcomes are consistent with Trzepieciński (2023), who emphasized that surface delamination and debris transfer can

induce dimensional drift in formed parts even when tool wear appears minimal.

Table 11. Coin weight conformity for different die systems (mean ± SD, 95% CI)

Material	Coins sampled ($\times 10^6$ coins)	Weight (Mean ± SD) (g)	95% CI (Coin weight) (g)	Out-of-spec weight (coins)
Uncoated DIN 2379	15.80	5.980 ± 0.032	[5.940, 6.020]	None
TiN on DIN 2379	7.60	5.990 ± 0.028	[5.955, 6.025]	None
CrN on DIN 2379	5.00	5.980 ± 0.029	[5.944, 6.016]	None
TiN on Böhler K490	4.93	5.790 ± 0.021	[5.764, 5.816]	2,500
CrN on Böhler K490	4.04	5.792 ± 0.034	[5.750, 5.834]	3,200

3.5.2. Edge Pass Rate and Defect Frequency

Edge quality results (Table 12) further distinguished DIN 2379 from K490. Uncoated and coated DIN 2379 consistently achieved edge pass rates of 99.998% with negligible defect rates (0.002%), and no dominant defect type was observed. These findings match Ľavodová et al. (2023), who linked coating durability to the preservation of edge sharpness in coinage dies.

In contrast, TiN- and CrN-coated K490 dies showed reduced edge pass rates (99.954% and 99.943%) and higher defect rates (0.046–0.057%), mainly irregular reeded edges caused by debris entrapment. Similar issues were documented by Smith (2022), who attributed increased rejection rates to oxide films and transfer layers from Cu–Ni planchets, rather than wear depth alone. These results reinforce that K490 performance was constrained by debris-induced instability.

Table 12. Edge pass rate and defect frequency for coins produced with different die systems

Material	Edge pass rate (%)	Defect rate (%)	Die wear depth (μm)	Dominant defect
Uncoated DIN 2379	99.998	0.002	20.600	Wear depth
TiN on DIN 2379	99.998	0.002	20.234	Wear depth
CrN on DIN 2379	99.998	0.002	20.806	Wear depth
TiN on Böhler K490	99.954	0.046	3.389	Debris
CrN on Böhler K490	99.943	0.057	2.783	Debris

3.5.3. Trade-off Between Die Life and Coin Quality

Taken together, Table 11 and Table 12 reveal a trade-off between apparent wear depth and product conformity. Although K490 dies terminated at shallow wear depths (~3 μm), they generated higher defect rates and out-of-spec weights, demonstrating that reduced wear does not guarantee better product quality. Comparable conclusions were drawn

by Trzepieciński (2023), who cautioned that debris accumulation can compromise dimensional accuracy even in low-wear conditions.

By contrast, TiN-coated DIN 2379 maintained excellent weight conformity and edge pass rates up to the 20 µm wear limit, while CrN-coated DIN 2379 delivered acceptable but shorter service intervals. These findings confirm that quality outcomes are governed by debris stability rather than wear depth. As also emphasized by Smith (2023), surface pickup and debris films can dictate product conformity more strongly than classical wear progression.

Overall, the results show that DIN 2379 systems ensure defect-free coin production until the defined wear threshold, while K490 systems, despite lower wear depths, were destabilized by debris. This reinforces the need to evaluate die systems not only by wear progression but also by their capacity to sustain weight stability and edge conformity under industrial minting conditions.

3.6. Economic Evaluation of Die Systems

The preceding results established that substrate–coating combinations influence hardness, adhesion, wear, and quality. However, industrial adoption ultimately depends on cost-effectiveness. An economic evaluation was therefore conducted, integrating die cost, effective life, and downtime losses.

Die procurement costs are summarized in Table 4, and effective die lives were taken from the observed outcomes in Section 3.4. Production output was defined as 650 coins/min with a setup time of 1.333 h per die change. Downtime losses were monetized at 5 Baht per coin, following the accounting framework used by the Royal Thai Mint, where downtime is expressed solely in terms of lost output value (Ithisoponakul et al., 2014). The results are shown in Table 13 and Fig. 19.

Table 13. Economic evaluation of die systems per one million coins

Material	Setup (h)	Die cost (Baht)	Downtime loss (Baht)	Total cost (Baht)
Uncoated DIN 2379	1.487	1,636	386,517	388,153
TiN on DIN 2379	0.669	1,004	173,949	174,953
CrN on DIN 2379	1.048	1,572	272,454	274,026
TiN on Böhler K490	1.015	4,769	263,777	268,547
CrN on Böhler K490	1.240	5,828	322,337	328,165

The analysis confirmed that downtime dominates the economics, representing more than 99% of total cost across all systems. This is consistent with previous reports that extending service intervals has far greater financial impact than procurement cost reductions (Ithisoponakul et al., 2014; Sousa & Silva, 2020). TiN-coated DIN 2379 achieved the lowest cost at ~175,000 Baht per million coins, less than half of uncoated DIN 2379 (~388,000 Baht) and significantly below CrN-coated DIN 2379 (~274,000 Baht). Although TiN-

coated DIN 2379 dies were slightly more expensive to manufacture (1,500 vs. 1,100 Baht), their longer service life reduced replacement frequency by ~55%, delivering the greatest savings.

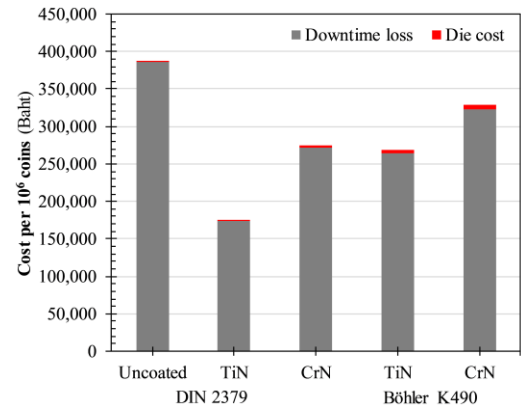


Fig. 19. Cost per one million coins for different die systems, divided into die cost and downtime cost

By contrast, Böhler K490 systems incurred higher costs (~269,000–328,000 Baht per million coins). The combination of higher procurement price and premature termination due to debris accumulation offset their higher hardness. These findings agree with earlier studies emphasizing that operational stability and extended service intervals outweigh material cost advantages in tooling economics (Navarrete et al., 2020; Sousa & Silva, 2020).

From an industrial standpoint, the results demonstrate that substrate–coating synergy, adhesion performance, and debris control are decisive for cost efficiency. TiN-coated DIN 2379 not only maximized die life and product quality but also minimized cost, confirming its suitability as the preferred option for high-volume coinage.

3.7. Overall Performance Evaluation

The integrated results highlight that tool performance in high-speed coinage is governed not by a single property but by the synergy between substrate, coating, adhesion, wear behavior, debris stability, and economic impact. DIN 2379, despite its lower hardness compared with Böhler K490, consistently outperformed in service life, coin quality, and cost efficiency when coated with TiN. Its effective die life of ~1.5 M coins, negligible quality defects, and lowest cost per million coins (~175,000 Baht) demonstrate that system-level balance – rather than individual material strength – determines success. Similar outcomes have been reported in stamping and coining applications where TiN delivered superior durability through its strong adhesion and resistance to catastrophic spallation (Fernandes et al., 2017; Sousa & Silva, 2020; Tavodová et al., 2023; Torsakul & Kuptasthien, 2024).

By contrast, Böhler K490, although harder (62.4 ± 0.5 HRC) and predicted by regression models to exceed 6 M coins, failed prematurely (~0.8–1.0 M coins). The cause was not wear progression but debris accumulation, driven by micro-asperity

interactions, coating–substrate mismatch, and adhesion-driven instability (Figs. 13–15). This divergence underscores that debris entrapment and third-body effects, as emphasized by Smith (2022) and Trzepieciński (2023), can dominate over classical wear criteria. As such, regression-only models proved inadequate for predicting K490 service life.

From a quality perspective, DIN 2379 maintained weight conformity (5.98–5.99 g, no out-of-spec coins) and edge pass rates of 99.998%, while K490 generated measurable out-of-spec weights (2,500–3,200 pieces) and higher edge defect rates (0.046–0.057%). These findings reinforce that stability against debris pickup, not wear depth, determines product conformity – consistent with tribological observations in forming processes (Smith, 2022; Trzepieciński, 2023).

Economically, downtime dominated total cost (>99% of losses), confirming that extending service intervals delivers disproportionate savings compared with procurement reductions (Ithisoaponakul et al., 2014; Sousa & Silva, 2020). TiN-coated DIN 2379 minimized total cost, whereas K490 systems, despite higher hardness, became costlier due to premature termination.

Overall, the evidence demonstrates that TiN-coated DIN 2379 provides the optimal balance of wear resistance, adhesion stability, debris control, product conformity, and economic efficiency. These findings highlight the importance of system-level evaluations that integrate microstructural, mechanical, tribological, and economic dimensions in tool performance assessment (Elghazaly, 2023; Navarrete et al., 2020; Schlegel & Schneiders, 2024).

4. Conclusions

This study systematically evaluated DIN 2379 and Böhler K490 collar dies, both uncoated and coated with TiN or CrN by arc-PVD, under industrial high-speed minting of Thai 5-baht coins. The main conclusions are:

- (i) Substrate–coating synergy is decisive. TiN-coated DIN 2379 achieved the best performance, sustaining ~1.5 M coins with negligible defects, while uncoated DIN 2379 failed at ~0.67 M coins. CrN extended life modestly (~0.95 M coins) but remained inferior to TiN.
- (ii) Debris governs K490 failure. Although Böhler K490 was harder (62.4 HRC) and predicted by regression models to exceed 6 M coins, premature termination occurred at ~0.8–1.0 M coins due to Cu–Ni debris accumulation. SEM/EDS confirmed pickup → agglomeration → debris bed pathways that destabilized dies before the 20 µm wear threshold, demonstrating the inadequacy of regression-only models. These findings indicate that adhesive junction growth and third-body formation – amplified by coating–substrate compliance and micro-asperity stress – govern the practical end of life in K490 systems rather than classical wear-depth progression.
- (iii) Product conformity depends on debris stability. DIN 2379 systems maintained weight conformity and >99.99% edge pass rates, while K490 produced out-of-spec weights (up to 3,200 pieces) and higher edge

defects (0.046–0.057%). Thus, quality loss was governed by debris instability, not groove wear depth.

- (iv) Economic efficiency is dominated by downtime. Downtime accounted for >99% of costs, confirming that extending service intervals yields far greater savings than reducing die procurement costs. TiN-coated DIN 2379 minimized cost (~175,000 Baht per million coins) and is recommended as the most cost-effective solution.

The novelty of this work lies in demonstrating that debris-induced instability, rather than substrate hardness or wear progression, governs die service life in high-speed coinage. Despite these insights, certain limitations should be noted. The number of dies per condition was limited to five, and only single-layer TiN and CrN coatings were examined, though multilayer or gradient coatings may provide enhanced adhesion and debris resistance. Regression analysis was restricted to groove wear depth, which proved insufficient to capture debris-driven failure modes. Future research should expand the die population for greater statistical robustness, investigate advanced coatings such as TiAlN, CrAlN, and multilayers, and develop debris-aware predictive models using FE–DEM or machine learning. Maintenance strategies such as groove refinishing or debris-clearing intervals also warrant study. Finally, extending evaluations to other coin denominations and planchet alloys would help generalize the findings beyond the Thai 5-Baht coin.

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