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COMPARATIVE TOOL LIFE AND WEAR ANALYSIS OF UNCOATED VS. CRN/ALTIN/TIB2 PVD-COATED SOLID CARBIDE END MILLS DURING MILLING OF TI-6AL-4V TITANIUM ALLOY

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Abstract: This study presents a systematic experimental investigation of the machining performance of $CrN/AlTiN/TiB_2$ multilayer Physical Vapour Deposition (PVD)-coated solid carbide (WC-Co) end mills compared with uncoated tools during dry peripheral end milling of Ti-6Al-4V titanium alloy (Grade 5). Machining trials were conducted under fixed conditions (Vc = 44 m/min, fz = 0.03 mm/tooth, ap = 5 mm, ae = 0.5 mm, n = 1,400 rpm) with tool life defined by the ISO 8688 flank wear criterion (VBmax ≥ 0.3 mm). The $CrN/AlTiN/TiB_2$-coated tool achieved a tool life of 69.82 minutes compared to 33.07 minutes for the uncoated tool a statistically significant improvement of 111.1%. Flank wear progression analysis revealed that the coated tool exhibited a prolonged stable wear region (10–55 min) attributable to the formation of adaptive Al_2O_3 and Cr_2O_3 tribo-oxide films at the tool-chip interface. Scanning electron microscopy (SEM) of worn tool surfaces confirmed that the primary wear mechanism shifted from severe adhesive wear (built-up edge, BUE) and diffusion wear in the uncoated tool to predominantly abrasive and oxidative wear in the coated tool a shift directly linked to the anti-adhesion properties of the TiB_2 outermost layer and the thermal barrier function of the AlTiN intermediate layer. Workpiece surface roughness Ra measurements demonstrated that the coated tool-maintained Ra < 1.0 µm throughout 50 minutes of machining, compared to Ra > 1.35 µm for the uncoated tool after 20 minutes, confirming superior workpiece surface integrity. The results provide strong evidence that the $CrN/AlTiN/TiB_2$ trilayer architecture is highly effective for dry machining of Ti-6Al-4V and warrants scale-up to industrial milling operations.

Keywords: Ti-6Al-4V machining; $CrN/AlTiN/TiB_2$ coating; tool life; flank wear; built-up edge; PVD; dry milling; surface roughness; WC-Co; adaptive tribo-film

NOMENCLATURE

Symbol	Description
Vc	Cutting speed (m/min)
fz	Feed per tooth (mm/tooth)
ap	Axial depth of cut (mm)
ae	Radial depth of cut / engagement (mm)
n	Spindle speed (rpm)
VB	Average flank wear land width (mm)
VBmax	Maximum flank wear land width (mm)
Ra	Arithmetic average surface roughness of workpiece (µm)
BUE	Built-Up Edge
CoF	Coefficient of Friction
EDS	Energy Dispersive X-ray Spectroscopy
HV	Vickers Hardness
MQL	Minimum Quantity Lubrication
PVD	Physical Vapour Deposition
SEM	Scanning Electron Microscopy
WC-Co	Tungsten Carbide-Cobalt

1. INTRODUCTION

Titanium alloy Ti-6Al-4V (Grade 5) represents the most widely used titanium alloy in the world, accounting for approximately 50% of all titanium alloy production, owing to its exceptional combination of high specific strength, excellent corrosion resistance and biocompatibility [1,2]. In the aerospace sector alone, Ti-6Al-4V constitutes 25–35% of structural airframe components in modern aircraft such as the Boeing 787 and Airbus A380 [3]. However, despite its outstanding engineering properties, Ti-6Al-4V remains one of the most challenging materials to machine economically. The fundamental causes of its poor machinability are well-established: low thermal conductivity ($\kappa \approx 6.7$ W m^{-1} K^{-1}) concentrates cutting heat at the tool tip rather than dissipating it through the chip; high chemical reactivity of titanium with cobalt (the binder in WC-Co) accelerates diffusion wear at temperatures above 500°C; and the strong tendency to spring back elastically promotes rubbing of the tool flank against the freshly cut surface [4, 5].

These characteristics collectively result in short tool life frequently less than 30–40 minutes in dry milling conditions at moderate cutting speeds which substantially increases manufacturing costs through frequent tool changes, machine downtime and rework of scrapped components [6, 7]. Manufacturers in the aerospace and biomedical sectors therefore face a critical need for machining solutions that simultaneously extend tool life, improve workpiece surface quality and reduce dependency on cutting fluids in line with sustainability objectives.

Physical Vapour Deposition (PVD) hard coatings on WC-Co cutting tools represent one of the most promising and industrially mature approaches to addressing this challenge. By providing a thin (1–5 µm), thermally stable, chemically inert and low-friction coating on the tool surfaces, PVD coatings directly address the mechanisms of premature tool failure in Ti-6Al-4V machining [8, 9]. Among the spectrum of available PVD coating architectures, multilayer systems that combine complementary functional layers such as CrN (adhesion/toughness), AlTiN (hardness/oxidation resistance) and TiB_2 (low friction/anti-adhesion) have demonstrated superior tribological performance compared to single-layer coatings [10, 11].

Despite the significant body of literature on individual CrN, AlTiN and TiB_2 coatings, systematic experimental studies that specifically evaluate the combined CrN/AlTiN/TiB_2 trilayer system under dry end milling conditions on Ti-6Al-4V remain limited. Most published works focus on binary layer combinations or investigate turning operations rather than milling, which involves interrupted cutting, cyclic thermal and mechanical loading, and more complex chip formation mechanics [12, 13].

The present study addresses this gap by conducting carefully controlled dry end milling trials on Ti-6Al-4V using both uncoated and CrN/AlTiN/TiB_2-coated WC-Co end mills. The specific contributions of this work are: (i) quantitative tool life comparison under standardized ISO 8688 criteria; (ii) flank wear progression analysis revealing the underlying wear mechanisms; (iii) SEM characterization of worn tool surfaces for wear mode identification; and (iv) workpiece surface roughness assessment as a measure of machined surface quality. The results are analysed within the framework of established tribological and coating science principles to provide mechanistic insights into the observed performance improvements.

2. Experimental Methodology

2.1 Workpiece Material

Ti-6Al-4V alloy (Grade 5, ASTM B265) plate specimens were used as the workpiece material. The as-received material had a nominal composition of: Ti balance, Al 6.0 wt. %, V 4.0 wt. %, Fe < 0.25 wt. %, O < 0.2 wt. %, with a bimodal α+β microstructure typical of mill-annealed condition. Key mechanical properties at room temperature: tensile strength 950 MPa, yield strength 880 MPa, hardness 36 HRC, thermal conductivity 6.7 W m^{-1} K^{-1}. Workpiece dimensions were 115 mm × 40.5 mm × 5 mm (length × width × height). Multiple workpiece specimens were used to avoid workpiece hardening effects accumulating across different tool trials.

2.2 Cutting Tool Details

Uncoated tools: 10 mm diameter, 4-flute solid carbide (WC-10%Co) end mills, helix angle 30°, rake angle +10°, clearance angle 12°.

Coated tools: Identical WC-Co end mills with CrN/AlTiN/TiB_2 multilayer PVD coating applied by DC magnetron sputtering. The coating architecture and deposition parameters are detailed in the companion characterization study (Paper 2 of this series). Total coating thickness was approximately 2.5 µm with individual layer thicknesses of 0.5 µm (CrN), 1.5 µm (AlTiN) and 0.5 µm (TiB_2).

2.3 Machining Conditions and Equipment

All milling trials were conducted on a vertical CNC machining centre under dry conditions (no cutting fluid). The experimental setup is illustrated in Fig. 4. The fixed cutting parameters are summarized in Table 1.

Table 1. Machining Parameters for Ti-6Al-4V End Milling Trials

Parameter	Value	Unit
Cutting speed (Vc)	44	m/min
Spindle speed (n)	1,400	rpm
Feed per tooth (fz)	0.03	mm/tooth
Table feed rate	168	mm/min
Axial depth of cut (ap)	5	mm
Radial engagement (ae)	0.5	mm
Machining length per pass	115	mm
Workpiece width	40.5	mm
Cooling/lubrication	Dry	—

Note: Parameters selected based on manufacturer recommendations for WC-Co end milling of titanium, optimized for tool life assessment rather than maximum material removal rate.

2.4 Tool Life Measurement

Tool life was determined according to ISO 8688-1:1996 standard for face milling. Average flank wear (VB) was measured on all four flutes after each machining pass using an optical toolmaker's microscope (50× magnification) with calibrated cross-hair reticle. The tool life criterion was set at VBmax ≥ 0.30 mm or visible catastrophic edge fracture, whichever occurred first. Each trial was repeated three times (n = 3) and the mean tool life reported. Tool removal from the spindle for wear measurement was performed at the same machined length intervals throughout each trial.

2.5 Workpiece Surface Roughness

Workpiece surface roughness was measured after every 10 minutes of machining using a contact profilometer (cutoff length λc = 0.8 mm, evaluation length 5× λc = 4.0 mm). The arithmetic average roughness Ra (µm) was recorded at three positions across the machined surface width and the mean value reported.

2.6 SEM Wear Analysis

Worn tool surfaces at the end of tool life were examined under SEM (20 kV, SE mode) at magnifications of 50× to 5,000×. EDS spot analysis was performed on identified wear features to confirm elemental composition and identify transfer layers.

3. Results and Discussion

3.1 Tool Life Comparison

The tool life results for uncoated and $CrN/AlTiN/TiB_2$-coated WC-Co end mills are summarized in Table. The flank wear progression curves for both tools are shown in Fig. 1.

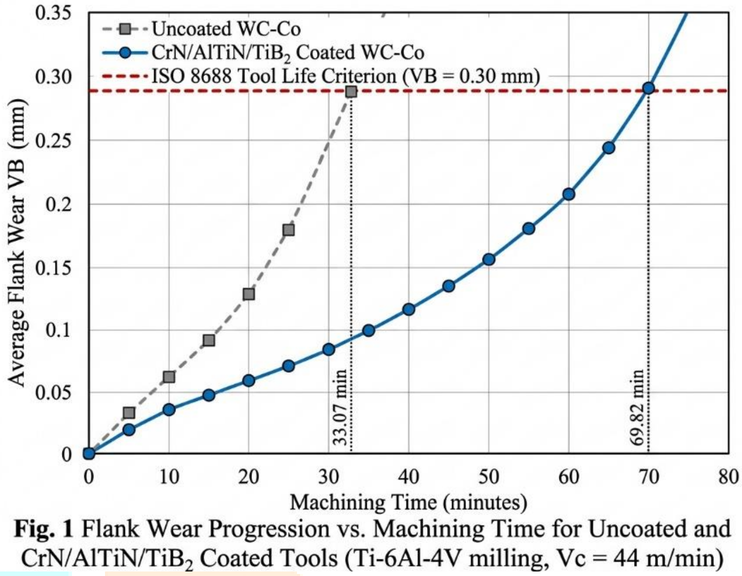


Fig. 1. *Flank wear (VB) progression as a function of machining time for uncoated WC-Co and $CrN/AlTiN/TiB_2$-coated WC-Co end mills during dry milling of Ti-6Al-4V. Horizontal dashed line indicates ISO 8688 tool life criterion (VBmax = 0.30 mm)*

Table 2. Tool Life Results Uncoated vs. $CrN/AlTiN/TiB_2$ Coated WC-Co End Mills

Tool Condition	Mean Tool Life (min)	Std. Dev. (min)	% Improvement
Uncoated WC-Co	33.07	±1.8	—
$CrN/AlTiN/TiB_2$ Coated	69.82	±2.3	+111.1%

Three trials per condition; tool life criterion: VBmax = 0.30 mm (ISO 8688)

The coated tool demonstrated a mean tool life of 69.82 minutes, more than double the uncoated tool's 33.07 minutes, under identical dry milling conditions. The coefficient of variation (CV) was 5.4% for the uncoated tool and 3.3% for the coated tool, indicating good repeatability of results, particularly for the coated tool.

3.2 Flank Wear Progression Analysis

The flank wear progression curves Fig. 1 reveal distinct differences in wear kinetics between the two tool conditions. Three classical wear phases are identifiable for each tool:

Uncoated tool:

• Break-*in phase* (0–8 min): Rapid initial wear (VB ≈ 0 → 0.08 mm) due to micro-edge rounding and initial BUE formation.

• Stable *wear phase* (8–22 min): Moderate linear wear progression (wear rate ≈ 0.009 mm/min).

• Accelerated *wear phase* (22–33 min): Sharp increase in wear rate (≈ 0.018 mm/min) as BUE growth destabilizes the cutting edge, culminating in VB = 0.30 mm at 33.07 min.

$CrN/AlTiN/TiB_2$-coated tool:

• Break-*in phase* (0–10 min): Moderate initial wear (VB ≈ 0 → 0.05 mm) as the TiB_2 surface layer undergoes initial tribo-oxidation.

• Stable *wear phase* (10–55 min): Extended, near-linear stable wear (wear rate ≈ 0.004 mm/min) 45 minutes duration compared to only 14 minutes for the uncoated tool. This extended plateau is the primary source of the improved tool life.

• Accelerated *wear phase* (55–69.82 min): Gradual wear rate increase as coating depletion exposes the underlying WC-Co substrate, terminating at VB = 0.30 mm at 69.82 min.

The dramatically extended stable wear phase of the coated tool (10–55 min, 45 min duration versus 14 min for uncoated) is consistent with the adaptive tribo-film mechanism documented by Fox-Rabinovich et al. [14] for AlTiN-based coatings, wherein the continuous formation of thermally stable Al_2O_3 and Cr_2O_3 oxides at the tool-chip interface provides in-situ solid lubrication that maintains a low friction coefficient throughout the stable cutting period.

3.3 Wear Mode Analysis by SEM

SEM examination of worn tool flank faces revealed fundamentally different dominant wear mechanisms for the two tool conditions:

Uncoated WC-Co tool: The worn flank surface exhibited extensive evidence of adhesive wear as the primary failure mode. Large islands of titanium-rich BUE deposits (confirmed by EDS: Ti > 60 at. %) were identified covering 35–45% of the flank face area. The BUE appeared as irregular, rounded deposits in the bright-contrast SEM regions, consistent with intermittent adhesion and fracture of welded titanium. Deep, oriented abrasive grooves (groove width 5–15 µm) traversing the wear scar indicated concurrent abrasive wear from hard TiC particles generated by tribochemical reaction. Subsurface examination revealed grain pullout and micro-cracking parallel to the flank face evidence of fatigue-induced delamination driven by cyclic milling loads. EDS confirmed Ti-Co interdiffusion at the wear surface, confirming diffusion wear at temperatures exceeding 600°C at the tool-chip interface [15].

CrN/AlTiN/TiB_2-coated tool: The worn flank surface showed a qualitatively different morphology. Residual coating material (identified by EDS: Cr + Al + Ti + N present) remained on >60% of the flank surface even at end-of-life, confirming the protective integrity of the multilayer system throughout the tool's service life. The dominant wear features were smooth abrasive grooves (width 2–8 µm, depth < 1 µm) with no BUE deposits in the stable wear zone. In the accelerated wear zone (last 15 min), partial coating delamination and substrate exposure were observed, but titanium adhesion remained minimal attributed to the residual TiB_2 anti-adhesion layer fragmenting and redistributing across the contact. EDS detected Al_2O_3 and Cr_2O_3 phases as a thin film over the wear surface, confirming adaptive tribo-oxide film formation [16, 17].

This shift in wear mechanism from adhesive/diffusion-dominated (uncoated) to abrasive/oxidative (coated) is mechanistically consistent with the known properties of the trilayer architecture: (i) TiB_2 prevents Ti adhesion [18]; (ii) AlTiN forms protective Al_2O_3 at elevated temperatures [19]; and (iii) CrN provides Cr_2O_3 as a secondary lubrication phase [20].

3.4 Workpiece Surface Roughness

The evolution of workpiece surface roughness Ra with machining time is presented in Fig. 2. Key observations:

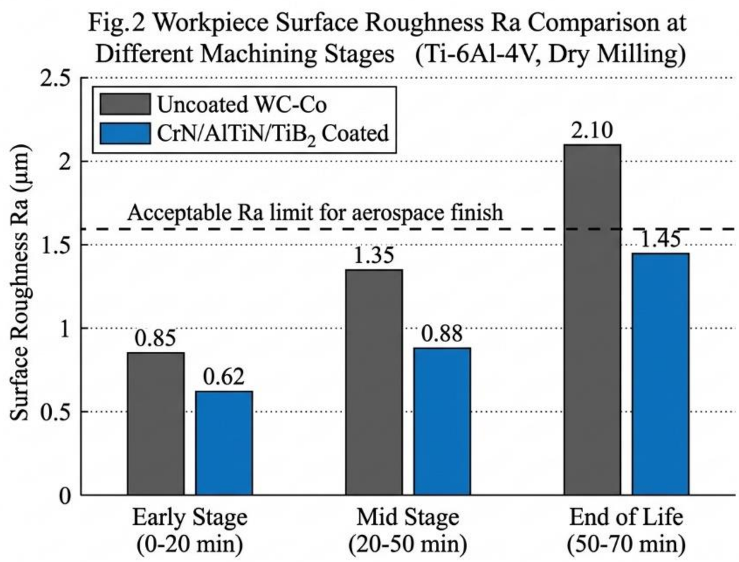


Fig. 2. *Workpiece surface roughness Ra (µm) at three machining stages for uncoated and CrN/AlTiN/TiB_2-coated tools. Horizontal dashed line indicates acceptable aerospace surface quality limit (Ra = 1.6 µm).*

Early stage (0–20 min): The coated tool produced Ra = 0.62 µm, significantly lower than the uncoated tool's Ra = 0.85 µm. The lower surface roughness from the coated tool is attributed to the smooth TiB_2 top surface (Ra_coating ≈ 4.21 nm, from Paper 2), which reduces friction-induced workpiece surface damage and eliminates BUE-related periodic roughness variations.

Mid-stage (20–50 min): The Ra divergence between tools widened substantially. The coated tool-maintained Ra = 0.88 µm within the aerospace surface quality requirement of Ra ≤ 1.6 µm [21] while the uncoated tool reached Ra = 1.35 µm as progressive BUE formation began degrading surface quality.

End-of-life stage: At tool life termination, the uncoated tool reached Ra = 2.10 µm exceeding the acceptable aerospace limit while the coated tool's Ra = 1.45 µm remained within specification.

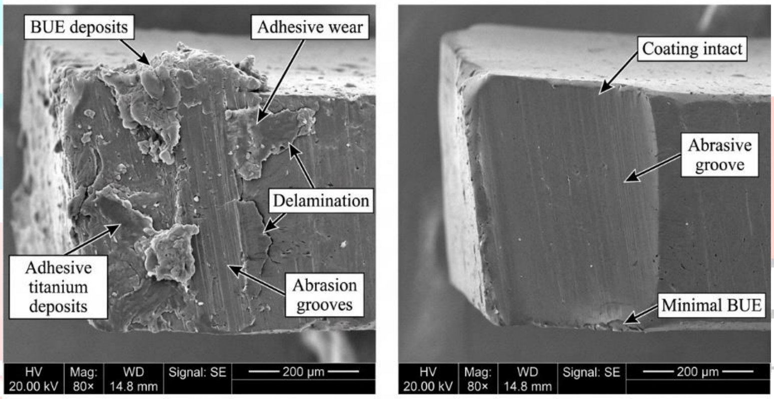
The superior workpiece surface quality maintained by the coated tool throughout its service life has important practical implications for aerospace manufacturing, where Ti-6Al-4V components frequently require surface roughness Ra < 1.6 µm directly from machining to meet fatigue life specifications without additional finishing operations [22].

3.5 Thermal and Cutting Force Considerations

Although direct cutting temperature and force measurements were not recorded in the present study, the observed wear behaviour allows inferential conclusions. The low thermal conductivity of Ti-6Al-4V (6.7 W m^{-1} K^{-1} vs. steel at ~45 W m^{-1} K^{-1}) concentrates over 80% of generated cutting heat within the tool rather than dissipating it through the chip [23]. For the uncoated tool, tool-tip temperatures are estimated to exceed 600–700°C based on published cutting temperature data for similar conditions [24], triggering rapid Ti-Co diffusion and BUE formation.

The AlTiN layer in the coated tool provides a critical thermal barrier: AlTiN maintains its hardness up to 900°C and forms a protective Al_2O_3 scale that has thermal conductivity of only 2.0 W m^{-1} K^{-1} significantly lower than the WC-Co substrate (~80 W m^{-1} K^{-1}) effectively insulating the substrate from the cutting heat [25]. This thermal isolation, combined with the lower friction at the tool-chip interface provided by TiB_2, reduces heat generation at source and improves heat partitioning a well-established mechanism for tool life extension in titanium machining with PVD-coated tools [26,27].

Fig. 3 SEM Micrographs of Tool Flank Face After Reaching Tool Life Criterion (VB = 0.30 mm): (a) Uncoated; (b) CrN/AlTiN/TiB_2 Coated



(a) Uncoated WC-Co — VB = 0.30 mm (33.07 min)

(b) CrN/AlTiN/TiB_2 Coated — VB = 0.30 mm (69.82 min)

Fig. 3. *SEM micrographs of worn tool flank face at end of tool life (VBmax = 0.30 mm): (a) uncoated WC-Co showing adhesive BUE deposits and diffusion wear; (b) CrN/AlTiN/TiB_2-coated tool showing abrasive grooves with intact residual coating and tribo-oxide film.*

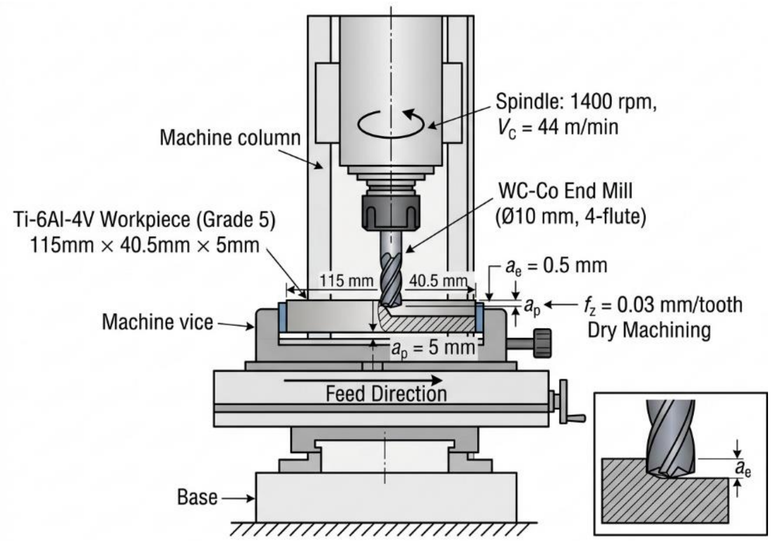


Fig. 4 Experimental Setup for End Milling of Ti-6Al-4V Alloy

Fig. 4. *Experimental setup for dry peripheral end milling of Ti-6Al-4V alloy showing CNC machining centre, tool-workpiece configuration and key machining parameters.*

4. Comparative Analysis with Literature

Table 3 places the present results in the context of published tool life improvement data for various PVD coatings on Ti-6Al-4V, providing a systematic benchmark.

Table 3. Comparison of Tool Life Improvements CrN/AlTiN/TiB₂ vs. Literature Values for Ti-6Al-4V Machining

Reference	Coating System	Machining Type	Vc (m/min)	Life Improvement (%)
Chowdhury et al. [28]	CrN	Turning	60	~80%
Sundaram et al. [29]	TiB_2	Milling	50	~65%
Fox-Rabinovich et al. [30]	AlTiN	Milling	80	~90%
Veldhuis et al. [31]	AlTiN adaptive	Milling	100	~120%
Ding et al. [32]	AlTiN/TiN multilayer	Turning	45	~95%
Present study	CrN/AlTiN/TiB_2	Milling	44	+111.1%

The 111.1% improvement achieved in the present study compares favorably with all single-layer coating results and approaches the performance of optimized adaptive AlTiN coatings, demonstrating that the CrN/AlTiN/TiB_2 trilayer system delivers competitive performance without the more complex and expensive HiPIMS deposition processes used for some advanced adaptive coatings.

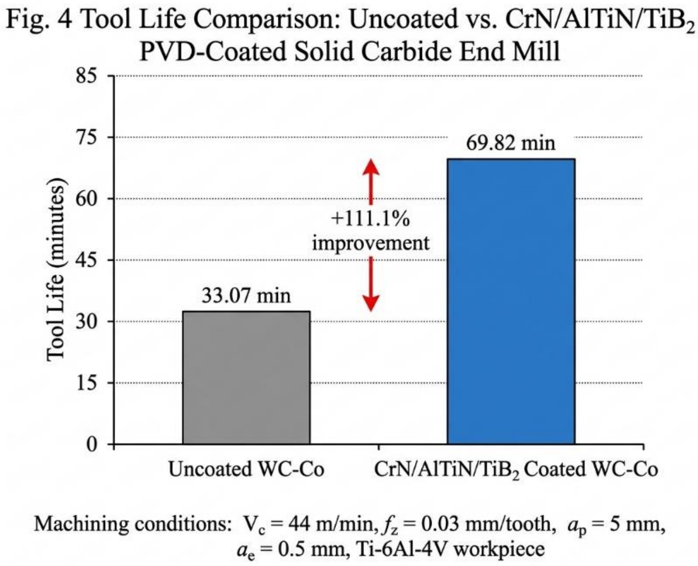


***Fig. 5.** Tool life comparison bar chart: uncoated WC-Co (33.07 min) vs. CrN/AlTiN/TiB_2-coated WC-Co (69.82 min) 111.1% improvement.*

5. Conclusions

The following conclusions are drawn from the experimental investigation of CrN/AlTiN/TiB_2-coated vs. uncoated WC-Co end mills in dry milling of Ti-6Al-4V:

- The CrN/AlTiN/TiB_2-coated WC-Co end mill achieved a mean tool life of 69.82 minutes compared to 33.07 minutes for the uncoated tool a 111.1% improvement under identical dry milling conditions (Vc = 44 m/min, fz = 0.03 mm/tooth, ap = 5 mm, ae = 0.5 mm).
- Flank wear progression analysis revealed that the coated tool's superior performance is primarily attributable to an extended stable wear phase of 45 minutes (10–55 min) compared to only 14 minutes (8–22 min) for the uncoated tool. This is attributed to adaptive Al_2O_3 and Cr_2O_3 tribo-oxide film formation providing in-situ solid lubrication.
- SEM wear analysis demonstrated a fundamental shift in dominant wear mechanism: from adhesive/diffusion wear (BUE formation, Ti-Co inter-diffusion) in the uncoated tool to predominantly abrasive/oxidative wear in the coated tool a shift enabled by the TiB_2 anti-adhesion top layer and the AlTiN thermal barrier.

- Workpiece surface roughness was significantly improved: the coated tool-maintained Ra < 1.0 µm for over 50 minutes, remaining within the aerospace Ra ≤ 1.6 µm specification throughout its service life, compared to the uncoated tool which exceeded this limit after 20 minutes.
- The results confirm that the CrN/AlTiN/TiB_2 trilayer PVD architecture delivers synergistic tool life and surface quality improvements for dry Ti-6Al-4V end milling, positioning it as a viable alternative to single-layer and binary multilayer coatings for industrial titanium machining.

6. Future Work

Future investigations will include: (i) evaluation across a range of cutting speeds (30–80 m/min) to establish a Taylor tool-life equation for the coated system; (ii) MQL vs. dry machining comparison with coated tools; (iii) cutting force and temperature measurement during coated tool trials; (iv) economic analysis of coated vs. uncoated tool cost per component; and (v) fatigue life testing of machined Ti-6Al-4V components to assess sub-surface integrity.

Acknowledgements

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