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Research on the Performance of AlCrSiWN Tool Coatings for Hardened Steel Cutting

Feng Guo *

Tianjin University of Technology and Education, Tianjin, China
* Corresponding Author: Feng Guo

ABSTRACT

This study compares the cutting performance of uncoated, as-deposited, and annealed AlCrSiWN-coated tools during dry machining of hardened steel. The uncoated tool failed within 8 minutes, exhibiting rapid wear (VBmax=300 μm) and thermal shock (5.2 °C/min). The as-deposited coating maintained steady wear (89.8-247.5 μm) for up to 60 minutes, but experienced abrupt wear acceleration to 569.7 μm at 90 minutes due to brittleness. The annealed coating extended wear life to 110 minutes with a final VBmax of 647.5 μm, demonstrating uniform wear progression and a 22% reduction in heating rate at 20 minutes. Temperature spikes (4.4-13.3°C/min) during severe wear correlated with expansion of the triangular wear band. Annealing effectively mitigated brittle fracture by facilitating plastic deformation, confirming its significant enhancement of coating durability under high-temperature cutting conditions.

KEYWORDS

AlCrSiWN Coating; Tool Wear Cutting Temperature.

1. INTRODUCTION

The addition of tungsten significantly influences the crystallographic and microstructural properties. Incorporating tungsten into CrSiN-dominated thin films can markedly enhance hardness [1] (increasing from 8.6 to 25.0 GPa) and Young's modulus (increasing from 208 to 320 GPa). Hones et al. prepared the $Cr_{1-x}Me_xN_\gamma$ system (Me = Mo, Ti, W, Nb) using reactive magnetron sputtering with Cr and corresponding Me targets, where $0 \leq x \leq 1$. Their study demonstrated [2] that both hardness and elastic modulus were higher in the selected range for tungsten additions compared to Mo, Ti, and Nb. Adding just 10% tungsten resulted in an 85% increase in hardness compared to CrN. Low amounts of tungsten in the CrN system lead to a texture change, shifting from a preferred (111) orientation to a weak (200) texture, while CrWN crystallizes in the cubic B1-NaCl structure. Increasing the tungsten content further alters the coating morphology, transitioning from a columnar structure to a fine-grained microstructure [3]. According to Hones' research, CrWN is most suitable for wear-resistant coatings because WN possesses high hardness, while CrN contributes to enhanced toughness. High-resolution transmission electron microscopy analysis revealed that the hardness increase is attributed to solid solution strengthening, resulting from differing atomic radii and reinforcement from isostructural superlattice nanolayers [4]. Chan et al [5] observed similar results, attributing the better wear resistance mechanism to the incorporation of nanostructured W_2N in the CrAlSiN system. Arc-evaporated AlCrSiWN coatings exhibited higher hardness (33.96 GPa) compared to AlCrN and AlTiN coatings, along with enhanced oxidation and corrosion resistance. (Al,Ti)N/a-Si_3N_4 composite coatings prepared by vacuum arc ion plating showed an initial hardness of 40 GPa. After annealing at 800°C, they displayed a self-hardening effect, with hardness increasing to 55 GPa, and delayed the dissolution temperature of the solid solution by 200°C. Adding tungsten can significantly improve the hardness and wear resistance of $CoCrFeNiW_x$ high-entropy alloy coatings [6], with optimal performance observed at $x = 0.8$. These coatings maintained stability and excellent wear resistance even after tempering. This study investigated the thermal stability and residual stress evolution of CVD (Al,Ti)N coatings during annealing using in-situ synchrotron radiation diffraction. The results indicate that annealing reduced tensile residual stresses at room temperature, improved the thermal stability of the coatings, and delayed the onset temperatures of spinodal decomposition and phase transformation reactions [7].

The significance of this research lies in providing scientific guidance for the manufacturing industry to optimize tool coating selection, thereby enhancing machining efficiency and product quality. By systematically analyzing the performance differences of various coated tools, this study aims to identify the most suitable coating solutions for specific workpiece materials and machining conditions, thus reducing production costs. Furthermore, the findings contribute to understanding the wear mechanisms of coated tools, offering theoretical support for the development of novel coating materials and advancing cutting technology toward higher precision and efficiency.However, the thermal stability of AlCrSiWN coatings under dry cutting conditions and the effect of annealing on wear mechanisms remain insufficiently explored.

2. ORGANIZATION OF THE TEXT

2.1. Experimental Instruments

Using arc ion plating technology, a nanoscale multilayer composite coating was deposited onto the substrate employing Al70Cr30 and Al52Cr28Si15W5 targets. For the deposition of the AlCrSiWN nanoscale multilayer coating, the base vacuum was evacuated to 3×10^{-3} Pa, with a deposition pressure ranging from 3 to 5 Pa, a pulsed bias voltage of -30 to -100 V, a substrate holder rotation speed of 1 to 2 r/min, a nitrogen gas flow rate of 1000 to 1500 sccm, a working pressure of 3 to 5 Pa, and a bias voltage of -40 to -100 V; the Al30Cr70 target utilized an arc current of 100-150 A while the Al52Cr28Si15W5 target used an arc current of 100-120 A, at a deposition temperature between 400°C and 480°C. The present invention fabricates a high-hardness AlCrSiWN nanoscale multilayer composite coating by adjusting the rotation speed to alternately deposit layers of AlCrSiWN and AlCrN.

This cutting experiment involved dry cutting of hardened mold steel (P20H) steel under identical cutting parameters, with comparisons made against Balzers' HELICA coated tools. During the experiment, cutting temperature, cutting force, flank wear width (VBmax), tool life was monitored to validate the cutting performance of different coated tools. The cutting was performed using a JOHNFORD-VMC-850 three-axis milling machine manufactured by Taiwan Johnford Machinery Industry Co., Ltd.

The workpiece materials selected were 45# hardened steel (58 HRC) The cutting parameters were set as follows: spindle speed 3183 r/min, feed rate 530 mm/min, cutting depth 9 mm (peripheral milling depth 1.5 mm according to GB/T 16460-2016), and cutting width 0.4 mm. A non-contact infrared thermal imager was used for temperature measurement.

The tool substrate was selected as a four-flute solid carbide cylindrical end mill (grade K44UF) from the same batch produced by CVE Tools Co., Ltd. Four tool types were tested: uncoated, AlCrSiWN-coated and AlCrSiWN-coated after annealing. Tool failure criteria, defined by GB/T 16460-2016 and JB/T 10231.1-2015, were VBmax reaching 300 μm, sudden increases in cutting force, chipping, or excessive sparking. A KEYENCE-VHX-1000 digital microscope was used to observe tool wear, ensuring data accuracy. The section headings are in boldface capital and lowercase letters. Second level headings are typed as part of the succeeding paragraph (like the subsection heading of this paragraph).

The annealing experiments on as-deposited coating samples were conducted using a TIANYOU TL200 extended dual-temperature zone vacuum tube muffle furnace to investigate coating thermal stability and enhance cutting performance, with a molecular pump drive controller maintaining vacuum below 3×10^{-3} Pa throughout the process. Samples placed in ceramic crucibles were centrally positioned in the furnace chamber for uniform heating, following initial evacuation to 2×10^{-3} Pa. Temperature profiles programmed via PID controller implemented heating to 600°C and multi-stage heating at rates ≤10°C/min, sustained isothermal conditions for 60 minutes, and controlled cooling at 3-5°C/min to mitigate coating thermal stress. The integrated water-cooling system maintained external furnace temperatures below 45°C, with routine post-operation maintenance performed on mechanical and vacuum extraction systems to ensure operational integrity.

2.2. Cutting Wear

Figure 1 shows that the uncoated tool reached the failure criterion of 300 μm wear land width (VBmax) within 8 minutes due to the lack of coating protection. For the as-deposited coated tool, the wear land width increased relatively steadily during the first 60 minutes. However, between 60 and 90 minutes, the wear growth slowed, increasing from 89.83 μm to 247.5 μm. Notably, the wear rate accelerated significantly at 90 minutes, with the wear land width sharply increasing to 569.73 μm, indicating coating failure. In contrast, the annealed AlCrSiWN-coated tool exhibited a more gradual increase in wear land width during the first 90 minutes, rising from 143.5 μm to 313.5 μm. This represented a smaller increase until a trend towards accelerated wear emerged at 90 minutes. By 110 minutes, the wear land width had surged to 647.5 μm, signifying coating failure. Compared to the uncoated tool, the as-deposited coating extended tool life by 775%. Based on the wear land width failure criterion (VBmax=300 μm), the annealed coating achieved a 28.57% longer tool life than the as-deposited coating.

Figures 2 and 3 reveal the wear morphology. For the uncoated tool at 8 minutes, lacking coating protection, the flank face exhibited plastic deformation. The wear land was relatively uniform, but edge chipping occurred at the tool tip, and significant adhesion (built-up edge, BUE) was observed on the bottom cutting edge. In the case of the as-deposited coated tool, the wear land displayed a distinctive triangular shape, wider at the bottom and narrower at the top, with non-uniform wear distribution. As cutting time progressed, adhesive wear became apparent on the coating surface, accompanied by extensive coating delamination, leading to gradual damage to the underlying tool substrate. Conversely, the annealed AlCrSiWN-coated tool showed milder wear within the first 90 minutes. While the central region of its wear land also exhibited the characteristic triangular shape (wider bottom, narrower top), the overall wear width was narrower and its distribution more uniform. Accelerated wear only commenced beyond 90 minutes. By 110 minutes, severe edge chipping and coating spalling were evident on the annealed tool. Overall, the annealed coating demonstrated more uniform wear characteristics, a relatively gradual progression in wear land growth, and consequently, superior wear resistance and extended service life.

2.3. Cutting Temperature

As shown in Figure 4, the uncoated tool exhibited the fastest temperature rise within the first 20 minutes, particularly reaching 5.2 °C/min between 5 and 10 minutes, then slowing to 0.8 °C/min. This indicates that the lack of coating protection accelerates thermal accumulation. For the three coated tools, temperature differences were insignificant in the first 20 minutes, with both annealed and as-deposited coatings showing similar slow heating rates. At 20 minutes, the as-deposited and annealed coatings provided approximately 23.17% and 22.27% thermal protection compared to the uncoated tool, respectively. The slight advantage of the as-deposited coating stemmed from its chromium oxide film, which effectively prevented direct oxidation of the WC-Co substrate at high temperatures, extending tool life in dry and high-temperature cutting conditions [8].

For the as-deposited AlCrSiWN coating, temperature gradually increased from 106 °C to 190 °C between 10 and 60 minutes, with a stable heating rate of 2 °C/min in the first 30 minutes, slowing to 0.4 °C/min between 50 and 60 minutes. Notably, temperature dropped from 190 °C to 185 °C (-0.5 °C/min) between 60 and 70 minutes. After 60 minutes of cutting, prolonged high temperature and friction induced plastic deformation on the tool surface, increasing workpiece adhesion. Accumulated built-up edge (BUE) from hardened steel, subjected to cyclic mechanical and thermal stress, cracked and detached, carrying away tool particles and accelerating coating delamination [9]. From 70 to 100 minutes, temperature surged to 301 °C, with a peak rate of 4.4 °C/min between 90 and 100 minutes. The widening triangular wear band indicated concentrated thermal and frictional stress, exacerbating coating wear as the protective layer spalled off.

The annealed AlCrSiWN coating showed a gradual temperature increase from 122.5 °C to 184 °C between 10 and 90 minutes, with notably slow heating rates (0.1 °C/min and 0.4 °C/min in the 30–40 min and 80–90 min intervals). However, temperature spiked to 333 °C between 90 and 110 minutes, with a dramatic 13.25 °C/min rate from 90 to 100 minutes. This acceleration resulted from enhanced adhesion and friction at high temperatures, promoting severe wear. The widening triangular wear band reflected concentrated frictional heating, where thermal accumulation compromised heat dissipation and exacerbated coating degradation. The study confirms that although annealing delays early-stage temperature rise, it cannot completely prevent rapid coating wear under high-temperature conditions.

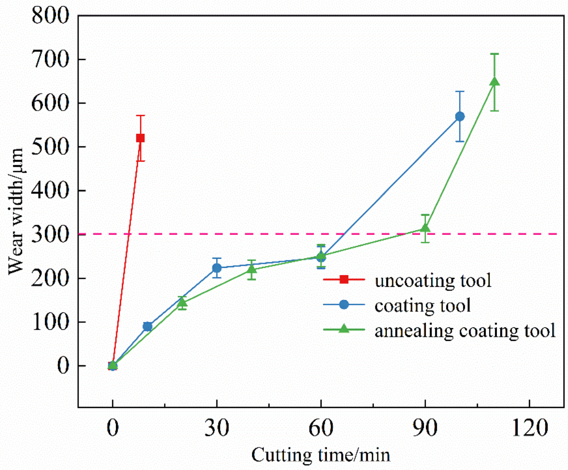

Figure 1. The uncoated tool reached the failure criterion of 300 μm wear land width (VBmax) within 8 minutes due to the lack of coating protection

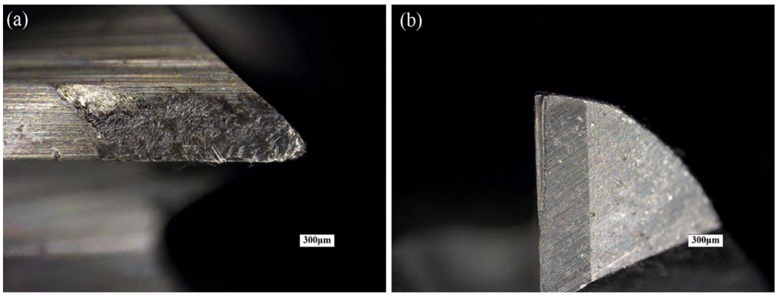

Figure 2. Wear of Uncoated Tools After 8 Minutes of Continuous Cutting: (a) Flank Face Wear Morphology; (b) Bottom Cutting Edge Wear Morphology

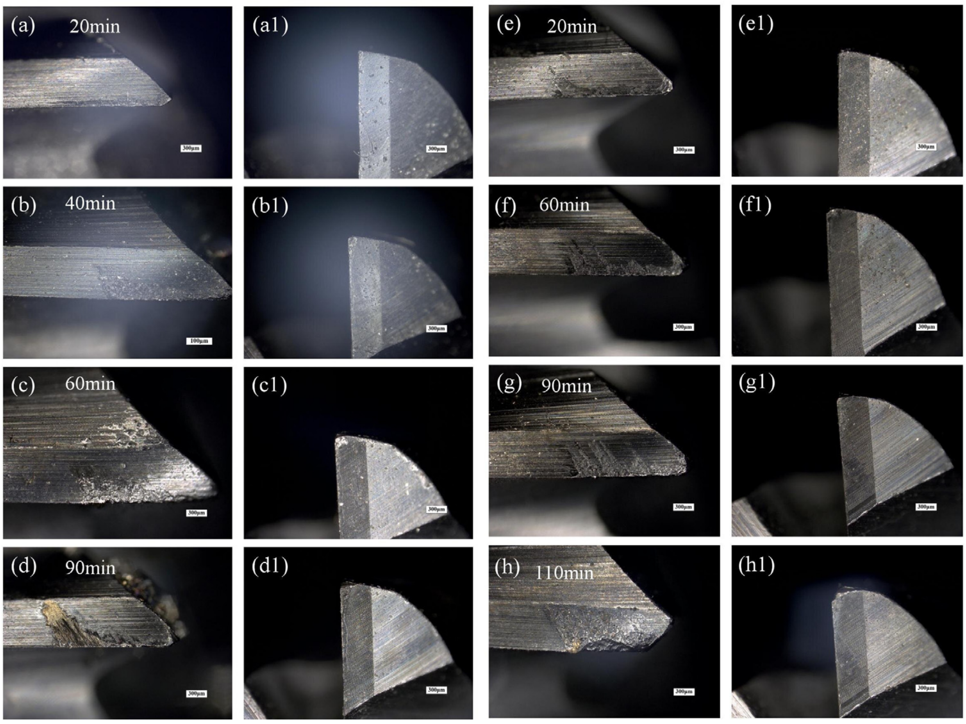

Figure 3. Morphology of Wear on (a,b,c,d) Side and (e,f,g,h) Bottom Cutting Edges of As-Deposited Coated Tools During Hardened Steel Cutting; (a1,b1,c1,d1) Side and (e1,f1,g1,h1) Bottom Cutting Edge Wear Morphology of Annealed Coated Tools

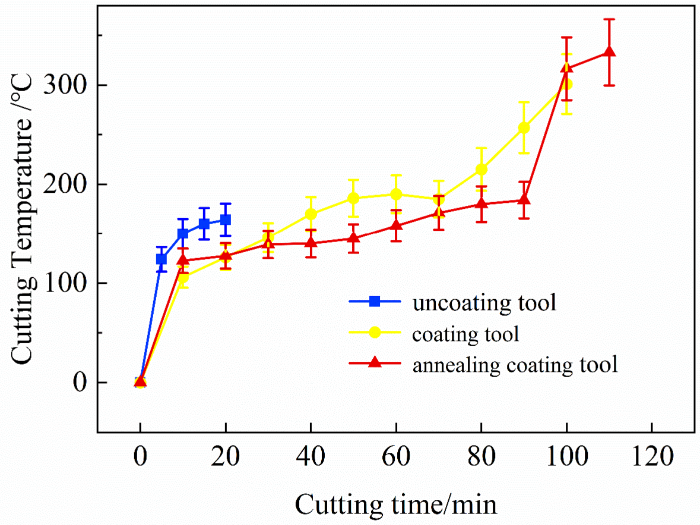

Figure 4. Comparison of Cutting Temperature Variation Among Uncoated Tools, As-Deposited Coated Tools, and Annealed Coated Tools at 600°C

3. SUMMARY

The optimal heat treatment process was selected to fabricate AlCrSiWN-coated tools. Cutting experiments were conducted to evaluate the performance of annealed AlCrSiWN-coated tools in comparison with uncoated and as-deposited AlCrSiWN-coated counterparts. Results show that during hardened steel machining, the annealed AlCrSiWN-coated tool exhibits significant advantages in tool life, achieving a 42.82% improvement over the as-deposited coating, along with lower cutting temperatures. When machining tungsten-molybdenum alloy, the annealed tool reaches the failure criterion (VBmax=300 μm) after 42 minutes of continuous cutting, with a maximum cutting temperature of 169 °C.

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