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THE DEVELOPMENT OF AN IMPROVED MULTILAYER CVD COATING FOR METALCUTTING APPLICATIONS

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Résumé - Un revêtement expérimental multicouche (Al₂O₃) a été appliqué sur des inserts d'outil de coupe en utilisant un équipement CVD de production automatisé. Les tests d'usinage d'acier 1045 révèlent une résistance à l'usure en cratère supérieure à celle de la couche monocouche (Al₂O₃). Cette résistance est fonction de l'épaisseur de ce revêtement. La résistance à l'usure en dépouille est proportionnelle à l'épaisseur de la couche sous-jacente (TiC et/ou TiC,N). Pour une épaisseur de 5 à 6 µm de cette dernière, l'outil expérimental présente une résistance à l'usure exceptionnelle.

Abstract - An experimental multilayer Al₂O₃ coating was applied to machine tool inserts using automated, production scale CVD equipment. In machine tests using 1045 steel, the experimental tool demonstrated crater wear performance superior to commercially available monolayer and multilayer Al₂O₃ grades. Resistance to crater wear was determined to be a function of Al₂O₃ coating thickness. Resistance to flank wear was found to be proportional to thickness of the backing layer (TiC and/or TiC,N). Thus, the relatively thick (5.5-6.0µm) backing layer of the experimental tool provided exceptional wear resistance.

I. INTRODUCTION

The primary benefit of various coating materials to the metalcutting performance of coated indexable WC-Co inserts has been well documented. Abrasion resistance (the most important consideration at lower cutting speeds) is provided by TiC (or TiC,N). Resistance to tool-workpiece chemical interaction (crater formation) is provided most commonly by Al₂O₃ due to this material having a very low free energy of formation. TiN is reputed to lower tool-workpiece frictional forces and the occurrence of edge build-up. In addition, its lustrous gold color enhances the marketability of the coated tool.

The combined benefits of these materials have been used to advantage in first generation multilayer coated tool inserts. Examples include the coating systems TiC/TiC,N/TiN and TiC/Al₂O₃/TiN. Additional benefits are expected for second generation multilayer coatings designed to achieve improved performance through optimization of layer thickness, number of layers, and the sequence of layer deposition.

The advantages of reduced grain size in CVD coatings applied to indexable WC-Co inserts are well known. The most commonly utilized method of reducing grain size in Al₂O₃ layers is to periodically interrupt the deposition of the Al₂O₃ layer by depositing a thin layer of TiC, TiC,N or TiN between the Al₂O₃ layers. In this way, each succeeding Al₂O₃ layer renucleates and grain growth is minimized. The advantages of this procedure were demonstrated by Dreyer and Kolaska [1].

Considerable improvements in flank wear resistance have been observed when cutting hot-worked steel (54 HRC), chilled cast iron and Inconel 718 with commercially available multilayered Al₂O₃ coated indexable inserts. These inserts utilized a ten layer coating consisting of TiC, TiC,N, TiN, and four layers of Al₂O₃ separated by three layers of TiN [2].

Improvements in both flank and crater wear performance have been demonstrated for a multilayer Al₂O₃ coated insert with an initial 3 micron thick layer of TiC overlaid by 19 layers of TiN and 19 layers of Al₂O₃ to a total thickness of 6 microns. When machine tested against conventional 6 micron thick TiC coated and 5 micron/1 micron thick TiC/Al₂O₃ coated inserts, the Al₂O₃ multilayered insert demonstrated superior crater and flank wear resistance in the machining of C60 steel. Superior performance of this Al₂O₃ multilayered coating was also observed during interrupted cutting of CK 45 KN steel [3].
It is the purpose of this paper to demonstrate the potential of our multilayer coating for the machining of mild steel. A companion paper documents the success of this coating for ductile iron machining [4].

2. EXPERIMENTAL METHODS

A computer-controlled, totally automated CVD coating unit of Kennametal design was constructed. This unit was used to prepare a number of complex, multilayered coatings.

The best of these coatings was selected for machine testing along with three commercially available TiC/Al₂O₃ or TiC/Al₂O₃/TiN coated grades and two commercially available Al₂O₃ multilayered grades. Throughout the text these will be identified as in Table 1, which is a compilation of coating thicknesses and compositions for the six coating/substrate combinations investigated. The WC-Co insert substrate for A, the experimental multilayered grade, was not cobalt-enriched and contained 6.0% Co, along with cubic carbides.

Coating thickness data were obtained by the wear scar method. This method entails making a small cylindrical wear scar through the coating and then measuring the exposed low-angle coating cross-section with an optical microscope. To determine coating thickness/wear relationships, the "measuring scar" was placed adjacent to the machine test "wear scar." In this way, errors due to coating thickness variability were minimized.

Microhardness values were obtained for the various coating layers and substrates by applying a low angle polish through the coating and traversing the coating with a series of Knoop indents made with a 100 gram load (which are preferred over Vickers indents to minimize underlayer or substrate effects [5]).

Optical microscopy was utilized to investigate coating microstructure. For the experimental coating, scanning Auger microscopy was utilized to determine the composition of the TiC₃N backing layer by traversing a low angle metallographic cross-section.

Continuous Turning of 1045 Steel

Metalcutting tests were conducted using measurable wear as the criterion for determining tool life. Thus, performance was related to wear properties of the tool such as crater wear, flank wear, nose wear, etc. In addition to the measure of performance relative to these tool life wear criteria, analysis of the "wear vs. time" curves showed the progression of wear.

A diagram showing the location of the various measured wear modes and corresponding failure criteria is shown in Figure 1.

Two styles of inserts and two test conditions were utilized:

<table>
<thead>
<tr>
<th>Test Conditions</th>
<th>CNMG 432</th>
<th>SNG 433</th>
</tr>
</thead>
<tbody>
<tr>
<td>1045 Steel</td>
<td>1045 Steel</td>
<td></td>
</tr>
<tr>
<td>260m/min.</td>
<td>260m/min.</td>
<td></td>
</tr>
<tr>
<td>0.38mm/rev.</td>
<td>0.38mm/rev.</td>
<td></td>
</tr>
<tr>
<td>2.0mm Depth of Cut</td>
<td>2.5mm Depth of Cut</td>
<td></td>
</tr>
<tr>
<td>-5⁰ Lead Angle</td>
<td>15⁰ Lead Angle</td>
<td></td>
</tr>
<tr>
<td>No Coolant</td>
<td>No Coolant</td>
<td></td>
</tr>
</tbody>
</table>

The complex rake geometry of the CNMG-432 style insert did not permit accurate crater wear measurements to be taken. For this reason, the CNMG-432 data were used merely to compare the relative tool lives of the various tools. SNG-433 style inserts were utilized to obtain an understanding of the wear mechanisms involved.

In both cases, the 1045 steel workpiece material was cut in an O.D. (outer diameter) turning pass on diameters varying from 150 to 75mm. The material was always pre-rough-turned with non-tested cutting tools to insure that all tested tool materials were provided with a clean, non-eccentric cutting condition from entry to exit of the cut. Time in cut was measured and the inserts were stopped at frequent intervals for measurement. In addition, to assure that all inserts were tested under identical conditions, the various experimental tools were run alternatively for the specified time period required for measurement. This assured that each tool material had cut over similar diameters and workpiece hardnesses in a random fashion to avoid introducing any bias due to the inherent variability in machinability of the workpiece material.
The relationship between individual coating layer thickness and flank and crater wear on SNG-433 inserts was determined by comparing the time required to reach specific wear values with coating layer thicknesses at each crater wear scar.

**Interrupted Cut Turning of 41L50 Steel**

This test was conducted in a manner to provide an interrupted cut with a progressively increasing degree of severity, which would ultimately result in failure of the cutting tool by fracture. This was accomplished by O.D. turning of a slotted steel workpiece material at a single condition of speed and depth of cut, but with the feed rate progressively increased after the successful completion of one hundred impacts. By its nature, this test provides an accelerated method of determining the relative edge strength of the tools which is rather independent of their wear resistance characteristics.

A diagram showing the workpiece configuration is shown in Figure 2. SNMG-433 style inserts were tested.

3. **EXPERIMENTAL RESULTS**

**Insert Characterization**

Figure 3 shows metallographic cross-sections of the coatings of the six tools investigated. Table 2 gives hardness data for the substrate, backing (TiC and/or TiC,N) layer and active (Al₂O₃ containing) layer. No particular relationships between substrate or coating hardness and insert performance were observed.

Figure 4 is a scanning Auger microprobe (SAM) line scan of the backing layer (TiC,N) of A, the experimental Al₂O₃ multilayer grade. Atomic percent Ti,N, and C levels were determined by quantitative analysis at four points along this scan. These points are included to give an approximate calibration. When added, the carbon and nitrogen concentrations exceeded 50% whereas the titanium averaged only about 41%. Because of the difficulty in separating the Ti and N peaks, it is possible that some of the titanium signal was interpreted as being nitrogen. No such problem exists with carbon determinations and the indicated concentration should be accurate within ±10%. Because of carbon diffusion from the substrate, the carbon level in the TiC,N backing layer was higher near the substrate, peaking at about 26 atomic percent. It declined to about 20.5% at the Al₂O₃/TiC,N interface.

**Wear Testing**

CNMG-432 style inserts failed mostly by nose wear in the continuous turning test. Only the C inserts failed by crater wear and were near the nose wear failure criterion (0.76mm) when the crater wear criterion (0.10mm) was reached. Because the dominant failure mode was nose wear, the various coating systems were compared using that criterion. Figure 5 shows the nose wear curve for A. It is typical of the type of plot used to determine nose wear life of all the grades. Figure 6 shows the ranking of CNMG-432 style inserts A through E with nose wear as the failure criterion. Although nose wear, a form of flank wear, was the predominant failure mode for the CNMG-432 style inserts, a strong crater wear component was undoubtedly involved. The complex geometry of the CNMG-432 style insert makes crater wear measurement very difficult. Additionally, the crater formed is very near the wear edge (usually within 0.7mm) and consequently, the various forms of flank wear are accelerated as the crater widens. For these reasons, it is likely that the accelerated nose wear observed was strongly influenced by cratering.

Figure 7 shows the crater-wear-versus-time relationship for SNG-433 style insert types A, B, B', C, and F. B' data are from a single corner of a B insert that had a much greater than normal Al₂O₃ thickness (12.9 microns). The SNG-433 style was selected because its simplicity of design (no chipbreaker grooves) permitted easier measurement of wear lands and cratering and therefore simplified analysis of the wear mechanisms involved. In all cases, the failure mode was cratering. By far the best performance, in terms of cratering, was with the B' insert which failed at 31.2 minutes. This superior performance was undoubtedly due to the abnormally thick Al₂O₃ layer. B inserts with nominal Al₂O₃ thickness (~6.7 microns) failed, on average, at 20.4 minutes. Essentially the same resistance to crater wear was achieved with the experimental tool (A).
The flank-wear-versus-time relationship for SNG-433 style inserts of types A, B, B', C, and F is shown in Figure 8. No D or E type SNG-433 style inserts were available at the time these tests were conducted. The average curves are shown without individual data points for clarity. The experimental A inserts demonstrated excellent flank wear resistance as did the C and F type inserts. The B and B' inserts showed relatively poorer flank wear resistance. In all cases, an increase in flank wear was observed as crater wear became severe. A correlation between the time to reach crater wear failure (Figure 7) and the upturn in flank wear (Figure 8) is apparent. All of the B type inserts, including B', showed rather poor flank wear resistance up to about 20 minutes. At this point, both the A and B type inserts showed an increase in flank wear rate (the C and F type inserts showed this upturn at about 15 minutes) whereas the B' insert showed no such increase until about 30 minutes. Apparently, as cratering became severe, rapid heating and deformation of the corner occurred and flank wear rate increased.

To better understand the relationship between coating layer thickness and wear resistance (uniform flank and crater), plots comparing coating thickness and wear were made for the SNG-433 inserts. Crater wear comparisons were made at the failure criterion of 0.10mm. Uniform flank wear comparisons were also made at 0.10mm which was well below the failure criterion of 0.38mm. This low flank wear value was selected to exclude the effects induced by advanced cratering.

Figure 9 shows the relationship between Al$_2$O$_3$ thickness and the time required to reach 0.10mm of crater wear (failure) for the SNG-433 style inserts. As Al$_2$O$_3$ thickness increased, crater wear resistance increased. Although the total Al$_2$O$_3$ thickness of the experimental A inserts was typically between 2.5 and 3.5 microns, the crater wear resistance was, on average, equivalent to a 5 micron thick monolayer of Al$_2$O$_3$. Also of interest are the large (~ 2/1) differences in crater wear resistance of the four tools tested. The variability in crater wear resistance noted for a particular Al$_2$O$_3$ thickness value indicates that there are factors other than Al$_2$O$_3$ thickness which affect crater wear. Backing layer (TiC and/or TiC,N) thickness and total TIN thickness showed no relationship to crater wear, indicating that these layers contributed relatively less in the way of crater wear resistance than did Al$_2$O$_3$.

Figure 10 shows the relationship between time to reach 0.10mm of flank wear and backing layer (TiC and/or TiC,N) thickness. As expected, flank wear resistance increased with increasing backing layer thickness. No relationship between Al$_2$O$_3$ thickness and flank wear resistance was observed.

Strength Testing

Figure 11 provides a ranking of the insert grades according to their edge strength at 107 and 198 m/min as determined by the slotted bar test. Values for C and D were estimated from previously conducted tests. All insert grades investigated showed an increase in impact strength, often as much as two to three times, at the increased surface speed. This is typical and is observed with most WC-Co grades. Superior edge strength was demonstrated for tools A and E.

4. DISCUSSION

The experimental multilayer coating (A) demonstrated better crater wear resistance than its Al$_2$O$_3$ thickness would have indicated. (Note that all three "A" points lie well above the typical performance line of Figure 9). This indicated that ~ 2.5um of multilayer Al$_2$O$_3$ yielded the equivalent crater wear resistance of over 5um of monolayer Al$_2$O$_3$. The most likely explanation for the improved performance is that the multilayer Al$_2$O$_3$ possessed a finer grain size than the monolayer Al$_2$O$_3$ which translated into improved crater wear resistance. However, the other multilayer grade tested (F) did not show a similar improved crater wear resistance. Other factors such as coating quality could explain this result.

Flank wear resistance (Figure 10) appeared to be solely a function of the backing layer thickness. There was no apparent relationship between backing layer composition (TiC, TiC/TiC,N or TiC,N) and flank wear resistance. The variability in flank wear resistance is believed to be attributable to inherent variations in the metalcutting test.

5. CONCLUSIONS

When compared in total (nose wear, flank wear, crater wear, and edge strength) the WC-Co indexable inserts with the experimental multilayer coating (A) showed great promise for commercial application in continuous and interrupted cutting of mild steels at high speed. Tailoring of the backing (flank wear resistant) and active (crater wear resistant) layer thicknesses and composition to the work environment make a wide range of applications possible for this tool. The utility of the backing and active layers in providing improved levels of specific types of wear resistance were demonstrated.
ACKNOWLEDGEMENTS

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LIST OF REFERENCES


4. Bryant, W. A.; Battaglia, F. B.; Downey, B. K.; Undercoffer, K. E.; The Metalcutting Performance of Multilayer Coated Tool Inserts, to be published 12th International Plansee Seminar.


<table>
<thead>
<tr>
<th>TABLE 1</th>
<th>NOMINAL COATING THICKNESSES AND COMPOSITION</th>
</tr>
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<tbody>
<tr>
<td>Insert Identification</td>
<td>Coating Thickness (microns) and Composition</td>
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<tr>
<td></td>
<td>Backing Layer</td>
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<tr>
<td>A$^2$</td>
<td>5.0um Ti(C,N)</td>
</tr>
<tr>
<td>B</td>
<td>3.0um TiC</td>
</tr>
<tr>
<td>C</td>
<td>6.0um TiC</td>
</tr>
<tr>
<td>D</td>
<td>5.7um TiC</td>
</tr>
<tr>
<td>E</td>
<td>2.8um TiC</td>
</tr>
<tr>
<td></td>
<td>2.0um Ti(C,N)</td>
</tr>
<tr>
<td>F</td>
<td>2.3um TiC</td>
</tr>
<tr>
<td></td>
<td>3.2um Ti(C,N)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>TABLE 2</th>
<th>COATING LAYER AND SUBSTRATE HARDNESS</th>
</tr>
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<tbody>
<tr>
<td>Insert Identification</td>
<td>Substrate Identification</td>
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<tr>
<td>A</td>
<td>1830</td>
</tr>
<tr>
<td>B</td>
<td>1720</td>
</tr>
<tr>
<td>C</td>
<td>1790</td>
</tr>
<tr>
<td>D</td>
<td>1750</td>
</tr>
<tr>
<td>E</td>
<td>1750</td>
</tr>
<tr>
<td></td>
<td>1750</td>
</tr>
</tbody>
</table>

1 Numbers in parenthesis denote number of layers.

2 Experimental multilayered Al$_2$O$_3$ grade (all others commercially available grades).

(1) Too thin to measure accurately.
(2) Average value for the two materials.
**Failure Criteria:**

- Uniform Flank Wear - 0.38 mm
- Nose Wear - 0.76 mm
- Crater Wear - 0.10 mm

**Work Material:**

- 41L50 Steel (slotted)
- Range of Cutting Diameters: 150 - 75 mm

**Figure 1.** Tool life measurement criteria.

**Figure 2.** Slotted bar configuration used to impact test SNMG-433 inserts.
Figure 3. Photomicrographs of the coatings of the insert grades investigated.
Figure 4. SAM C, N, and Ti line scans of backing layer (TiC,N) of experimental insert A.

Figure 5. Nose wear as a function of machine test time for CNMG-432 experimental inserts A.
Figure 6. Time-to-failure by nose wear for CNMG-432 inserts.

Figure 7. Crater wear as a function of machine test time for SNG-433 inserts.

Figure 8. Uniform flank wear as a function of machine test time for SNG-433 inserts.
Figure 9. Crater wear relationship to Al2O3 thickness for SNG-433 inserts. (Ordinate points from Figure 7 data.)

Figure 10. Flank wear relationship to backing layer (TiC and/or TiC,N) thickness for SNG-433 inserts. (Ordinate points from Figure 8 data.)

Figure 11. Impact strength of SNMG-433 style inserts.