Influence of the coating residual stresses on the tool wear

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Abstract

The use of PVD (Physical Vapor Deposition) coatings is one of the most common methods to improve the performance of the cutting tools, reducing the wear under heavy loads and high temperatures. A key aspect to increase the tool life is the control and development of the PVD process.

In this work different turning inserts have been coated with two different coatings (ZrCN and TiN) and four different bias voltages (30, 120, 210 and 400 V). The residual stresses in the coated tools have been measured in the clearance face near tip of the tool zone using grazing incidence X-ray diffraction.

In order to analyze the performance of the coated tools and the relation residual stresses-tool life, machining tests have been performed with two steel grades, AISI 1045 and AISI 4340. The results show that the tool wear is directly related to the residual stresses of the coatings, and these can be controlled by the bias voltage.

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1. Introduction

Industrial sectors demand highly efficient and cost effective production of mechanical components, pushing the improvement in the field of machining processes [1]. Coating technology is one means for improve the cutting tool performance, but the coating process is affected by several aspects such as coating material, structure and process conditions; a suitable selection of these factors should drive to an improvement in the machining process. PVD technique is the most common technique to improve the performance of the cutting tools, and it has some advantages compared to CVD processes [1]: Lower

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process temperature allowing the carbide toughness to be maintained, generation of compressive residual stresses that inhibits crack propagation, and it can be applied to sharp cutting edges.

The residual stresses in coatings are a result of structural and thermal components. The structural stresses are due to strains created by increasing the layer thickness and the defects built into the coating; while the thermal stresses are a consequence of the mismatch in thermal expansion coefficient of the coating and the substrate [2].

The high level of compressive residual stresses in PVD coating can have a beneficial effect of increasing the wear resistance and the hardness, but too high residual stress may reduce the adhesion and produce delamination due to the embrittlement of the coating [3]. The characteristics of the PVD coating are a result of the process conditions such as bias voltage, gas pressure, arc current and temperature [4].

In this paper the influence of the bias voltage, on the residual stress and the thickness of the coatings, is analyzed. The effect of ZrCN and TiN PVD coatings characteristics on the tool wear resistance is assessed for the machining of two steels: AISI 1045 and AISI 4340.

2. Experimental systems

2.1. PVD coatings

The TiN and ZrCN PVD coatings were deposited by cathodic arc evaporation method in the industrial equipment MIDAS 775 developed by Tekniker. This system has 12 circular evaporators of 100 mm and a working intensity range of 60-140 A. In the cleanliness step, before the coating deposition process, the samples were sprayed with a solvent product and cleaned in an alkaline detergent by means of ultrasounds method. When samples were loaded into the chamber, they are heated up to a substrate temperature of 400-500 ºC. Then a cleanliness named Glow Discharge was applied to them. Before deposition of the coating an adhesion layer is applied to the substrates (20 nm of Ti and Zr respectively). The reactive gases used in the process were nitrogen and acetylene in order to form the nitride and carbon nitride films. Ti and Zr targets for the arc evaporator were used. The chamber pressure before starting to coat was $10^{-6}$ mbar and the pressure supported during the deposition process was kept between $10^{-2}$-$10^{-3}$ mbar. The coating process was carried out maintaining the process time at 4 different bias voltages: -30, -120, -210 and -400 V. Each coating process was repeated 3 times. The thickness of the coating was measured using the spherical calotte test in steel samples coated in the same run of the cutting inserts.

2.2. Residual stress measurements

Although the sin$^2$Ψ method [5,6] is the most widely used residual stress calculation method, the residual stresses in the coated inserts were measured using grazing incidence X-ray diffraction (XRD) using the g(Ψ,hkl) method [7] for a biaxial stress state, assuming no stress gradients in the z (depth) direction. This method was used because the sin$^2$Ψ method could be inappropriate if the coating material diffraction peaks overlap those of the tool substrate material. On the other hand the intensity of the diffraction peaks due to the coating is improved as grazing incidence allows obtaining data with a lower penetration thickness of the X-ray in the material. A Bruker D8 Advance X-ray diffractometer equipped with Cr radiation (X-ray wave length $\lambda_{Cr}=2.291$ Å) and parallel beam was used to perform the residual stress measurements. 5 reflections corresponding to {hkl} Miller indices {111}; {200}; {220}; {311} and {222} were measured for each coating. Grazing incidence angle was 2º for ZrCN and 3º for TiN. The X-ray crystallographic constants for each peak were obtained from reference [8] (ZrCN) and [9] (TiN) while stress free atomic interplanar spacing was obtained from ICDD database: ID 035-0753 (ZrN) and ID 038—1420 (TiN).
The coatings were considered homogeneous and any preferred residual stress direction was identified. The measurements were carried out in the flank face of the tool near the edge of tool in the machining area.

2.3. Machining tests

The work piece materials were AISI 1045 (199 HBW 2,5/187,5) and AISI 4340 (350 HBW 2,5/187,5) steels. The machining tests were done on a CNC CMZ TL-15M lathe (5000 rpm, 14 Kw). Tool flank wear (VB) was measured with a contact microscope.

Table 1. Cutting conditions for the tool life testing

<table>
<thead>
<tr>
<th>Material</th>
<th>Cutting Speed. $v_c$ (m/min)</th>
<th>Feed per revolution. $f_n$ (mm/rev)</th>
<th>Depth of cut. $a_p$ (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AISI 1045</td>
<td>250</td>
<td>0.07</td>
<td>0.8</td>
</tr>
<tr>
<td>AISI 4340</td>
<td>275</td>
<td>0.085</td>
<td>0.8</td>
</tr>
</tbody>
</table>

The tests consisted of continuous external turning under dry cutting conditions; the cutting parameters are shown in the table 1. The tool life criterion used in the tests to evaluate the machining performance has followed the ISO 3685:1993 standard by measuring the VB (Flank wear); the 0.3 mm limit was not reached in the cutting tests because the duration was limited to 10 minutes, evaluating the VB value at that time. The values reported in this work are the average for 2 repetitions with each tool of the 3 coating process repetitions, resulting in 6 tests for each condition.

The tools used were uncoated WC inserts with grade UTi20T from Mitsubishi, equivalent to ISO P30. The insert geometry was CNMG120408, and the tool holder reference was DCLNL2525 M12 with double clamp system. The final set-up has the following characteristics: Approach angle ($\psi_r$): 95°; Side rake angle ($\gamma_f$): -6°; Back rake angle ($\gamma_p$): -6°; Clearance angle($\alpha_f, \alpha_p$): 6°.

3. Results and discussion

3.1. Coating characterization

Figure 1 shows the residual stress and thickness measurements of the coatings. Both coatings, ZrCN and TiN, show differences in the measured values as the bias voltage changes. Analyzing the repeatability, qualitatively the results are consistent, but some differences are noticed from a quantitative point of view.

The ZrCN coatings show a maximum compressive residual stress at -120 V; the tendency seems to be a V shaped curve as the bias voltage increases. In the case of TiN coatings the tendency is not so clear, and the compressive residual stresses seem to decrease as the bias voltage increases, with a constant transition zone between -120 and -200 V.

In the case of TiN coating, the measurements of the series 3 for -200V and -400V seem to introduce significant error and to be out of the general tendency, so this is attributed to experimental measurement error.

The non-linear behavior of the residual stresses has been observed by other authors [10], these indicate that the inflection point (residual stress vs. bias voltage) could be a consequence of an increasing importance of the structural component in the generation of the residual stresses.

Regarding the coating thickness, this also varies with the changes in the bias voltage. For the ZrCN coating, the thickness follows a tendency similar to the residual stress, being the coating thicker as the
residual stresses are more compressive. For the TiN coating, the thickness remains practically constant for -30 and -120 V, and then it decreases as the bias voltage increases.

![Graph](image)

Fig. 1. Residual stress and thickness measurements. (a) ZrCN coatings; (b) TiN coatings

The behavior of each coating as the bias voltage change is different. As a general rule, the thickness and compressive residual stress decrease as the bias voltage increases. The -120V bias voltage is an inflection point in both coatings, being this more pronounced in the case of ZrCN.

3.2. Machining results

Figure 2 shows the results of the average VB (t=10 min) for the three series of ZrCN coating in the turning of both steel grades. The general behavior is similar for the three series. It can be noticed that the thickness, residual stress and flank wear curves follow similar tendencies; so it seems to be a direct relation among them: The compressive residual stresses are higher for the thicker coatings, and a higher value of the compressive residual stresses results in a higher VB and shorter tool life.

![Graphs](image)

Fig. 2. Residual stress, thickness and VB (t=10 min) results for the ZrCN coatings in AISI 1045 and AISI 4340 turning.

In the machining of AISI 4340, it can be seen that ZrCN coating with -30V of bias voltage suffers the highest flank wear. These tools do not follow the general behavior described above, being the tool wear
high despite the lower value of compressive residual stresses. This behavior could be a consequence of the adhesion of the coating, becoming a critical factor during machining of AISI 4340 due to the higher mechanical loads compared to the machining of AISI 1045. Figure 3 shows the characteristic tool wear of the tested cutting inserts. The short transition zone and the step, between the coating surface and the substrate of the tool, indicates a fragmentation and delamination of the ZrCN (−30V) coating in the figure 3a possibly due to poor adhesion of the coating; while figure 3b shows abrasive wear marks in a wide transition zone for the ZrCN (-120V, -200V, -400V) coatings.

Figure 4 shows the results of the VB (t=10 min) for the three series of TiN coating in the turning of both steel grades. The behavior is different to that observed in the ZrCN coated tools. The change in the bias voltage affects the thickness and residual stresses, but these have little influence on tool wear and only small differences are noticed. However, the general tendency observed in the ZrCN coatings can be observed in TiN coatings too: higher thickness, higher compressive residual stress and higher wear.

In this case, the machining of AISI 4340 also results in the worst behavior against wear for the TiN coating with -30V of bias voltage, but it cannot be noticed any different behavior in the tool wear pattern. The abrasive tool wear, as shown in figure 3c, is similar for all the bias voltages used in the TiN coatings.

The series 1 produce higher tool wear than the other series in the machining of AISI 1045, and also variable results in the machining of AISI 4340. There is not any clear explanation to this behavior.

Fig. 3. Characteristic tool wear for (a) ZrCN (-30V), (b) ZrCN (-120, -200, -400V), (c) TiN (-30, -120, -200, -400V).

Fig. 4. Residual stress, thickness and VB (t=10 min) results for the TiN coatings in AISI 1045 and AISI 4340 turning.
In both coatings, ZrCN and TiN, the behavior of flank wear and residual stress is opposite to those reported by other authors [2, 3]. These have noticed that the compressive stresses become tensile in use, being the tensile stress the reason of the damage in the coating. Thus, a higher compressive stress should improve the resistance of the layer to cracks, wear and corrosion.

4. Conclusions

In this work the residual stresses of ZrCN and TiN coating on WC tool were analyzed. It was determined the influence of the coating conditions, bias voltage, on the residual stresses and the wear behavior in machining processes. The initial surface compressive residual stresses state for the uncoated tools, -281 MPa, changes to highly compressive residual stresses state after the coating deposition; the residual stress values are in the range from -4.58 GPa to -7.99 GPa for the ZrCN coating and from -5.8 GPa to -11.44 GPa for the TiN coating. The different bias voltage values used in the coating process affect the thickness and the residual stresses in the deposited layer; and these can be correlated with the wear resistance of the tools in machining tests.

Turning test were carried out in AISI 1045 and AISI 4340 workpiece materials. The main conclusion is that the compressive residual stresses are higher for the thicker coatings; and as a general trend, a higher value of the compressive residual stresses results in a higher flank wear (VB) and shorter tool life. This behavior is opposite to that reported by other authors [2,3].

The machining tests also reveal that the adhesion for the ZrCN coatings at -30 V bias voltage is poor, resulting in the delamination of the coating instead of abrasive wear.

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