Residual Stress in PVD-Coated Carbide Cutting Inserts - Applications of the $\sin^2\psi$ and the Scattering Vector Method

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Abstract. Premature collapse in terms of cohesive damage of PVD-coated carbide cutting tools often results in a time and cost consuming immediate interrupt of the cutting process. It is assumed that the residual stress state of the composite coating – substrate in combination with external loads during tool use is responsible for cohesive damage. The X-ray diffraction methods $\sin^2\psi$ and scattering vector are applied for determination of the residual stress depth distribution in the coating and the substrate’s subsurface. Investigations of the residual stress state of commercial PVD-coated carbide cutting tools are presented. It is determined to what extent the single process steps during tool manufacturing are responsible for the final residual stress state of the PVD-coated tool. Furthermore the meaning of the PVD-coating process for the substrate’s residual stress state is investigated. Moreover, possibilities of controlling the residual stress state of the substrate by changing process variables of selected process steps are analyzed.

Introduction

Compressive residual stress in the subsurface increases lifetime of technical components which are exposed to alternating loads [1,2,3]. This is also valid for cutting tools, where a compressive residual stress state is induced by processes like grinding or blasting. In PVD-coated tools the coating possesses high compressive residual stresses in the range of several GPa. These can be detected non destructively by X-ray diffractometry, most commonly by the application of the $\sin^2\psi$ method [4]. By this, depth resolved residual stress investigations in the surface near region can be carried out with relatively high efforts, and only in discrete depths [5,6].

In contrast the scattering vector method enables the determination of continuous depth resolved residual stress measurements from the surface to the maximum penetration (better: information) depth $\tau_{\text{max}}$ [5]. This is possible by a continuous rotation of the specimen through the scattering vector $g_{\psi\varphi}$ at different tilting angles $\psi$ (fig. 1), for which a special 5-axes goniometer is required.

By this method residual stress depth distributions of laboratory prepared CVD- and PVD-coatings [5,7,8,9,10] and those of commercial PVD-coated carbide cutting tools have been determined [11,12,13] (fig. 2). A combination of depth resolved residual stress measurements of the coating and the substrate’s subsurface gives information about the overall residual stress gradient of that tool region, which is most loaded during tool use [14] (fig. 3).

Near the interface there exists a range with tensile residual stress in the substrate, which may lead to a chipping of the coating during additional external tensile load, the so called cohesive damage. In order to avoid this kind of damage it is necessary to understand the development of residual stress during tool manufacturing and to know about the possibilities of influencing it by changing process parameters.
Fig. 1: Schematic diagram of the scattering vector method

- Fig. 2: Residual stress depth distributions of different PVD-coatings

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**Fig. 1**

- **P1, P2, P3**: specimen coordinate system
- **PS**: primary beam
- **SS**: secondary beam
- **2θ**: Bragg angle
- **g_φψ**: scattering vector
- **N_hkl**: normal of netplane hkl
- **ψ**: tilting angle
- **φ**: angle of rotation by sample normal
- **η**: angle of rotation by scattering vector

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**Fig. 2**

- **A**: 3 μm Arc-PVD Ti_{0.85}Cr_{0.15}N on HSS
- **B**: 5 μm PVD TiN on HSS
- **C**: 5 μm PVD TiN on HSS, Bias = 0 V
- **D**: 5 μm PVD TiN on HSS, Bias = 200 V, at half coating thickness Bias = 0 V
- **E**: 3.4 μm PVD (Ti,Cr)N on HSS
- **F**: 1.4 μm PVD (Ti,Cr)N + 1.4 μm PVD TiN + 0.2 μm TiN on HSS
- **G**: 1.4 μm PVD TiN + 1.4 μm PVD (Ti,Cr)N + 0.2 μm TiN on HSS

**Sources**: [5,9,10,11,12,13]
Development of Residual Stress During Tool Manufacturing

In order to determine, which process step is responsible for the residual stress state of the carbide substrate, tools from different suppliers have been taken from commercial processes after each process step. Residual stress has been measured at each of the 4 flank faces, applying the $\sin^2 \psi$ method. Fig. 4 in the left part shows typical results of these investigations. The absolute values may vary, but the influence of each step on the previous one is comparable.

After sintering the specimens are nearly stress free, with a trend to compressive stress. Suitable grinding processes induce compressive stress of about $\sigma = -450$ MPa. The mechanic energy that is induced by the blasting process increases the compressive stress to about $\sigma = -800$ MPa. Etching shows a temperature effect and additionally sets back the cobalt matrix relieving the WC grains, which expresses itself in a reduction of compressive stress to values of about the level before blasting. Finally the PVD-coating process again reduces compressive stress about 20%, which cannot be explained without further investigation.

In order to determine the cause for the compressive stress reduction during PVD-coating, a set of 8 cutting inserts has been taken from the process chain after etching, and residual stress has been determined by the $\sin^2 \psi$ method at all 4 flank faces. 4 tools are coated as usual, while the remaining 4 are enwrapped in a stainless steel foil. All of them undergo the same process within the same batch. After this procedure residual stress is determined again. The etched specimens show a mean of $\sigma = -600$ MPa, the coated ones a reduction of about 22% to $\sigma = -470$ MPa. Those tools which had been enwrapped also show a stress reduction, but only about 10% to $\sigma = -540$ MPa (fig. 4, right).

Both tool series encountered the elevated coating temperature of several hundred degrees Celsius for 2 hours. This is responsible for a residual stress reduction of about 10%. The remaining reduction of 12% at the coated tools must be a result of a clamping effect by the coating itself with its high compressive stress. A further indication for this can be seen in the fact of a slight increase of compressive stress after a chemical decoating, though the effect in this direction is only very small [14].
Impact Depth of Compressive Residual Stress in the Substrate’s Subsurface

Scattering vector measurements with Cu Kα radiation show that the impact depth of the compressive stress in the substrate’s subsurface is limited to very surface near regions [14]. For the prevention of premature tool damage as a result of tensile stress it is desirable to bring stronger compressive stress into greater depths. How far this is possible by a simple parameter variation of those processes, used for the fabrication of the tools, is shown in the following. The residual stress measurements are performed by the sin²ψ method. As by absorption of the X-rays the information depth is less than \( \tau = 2 \) µm, the stress depth distributions are obtained by gradual electrolytical polishing before stress measurement.

Grinding Process, Variation of Axial Feed. In a series of experiments the flank faces of carbide cutting inserts have been ground with different axial feeds in the range of 2 – 20 mm/min. In the surface residual stress values between \( \sigma = -1000 \) and -1200 MPa are found. The depth distributions show an impact depth of about 6 µm, independent of the axial feed (fig. 5).

Blasting Process, Variation of Blasting Pressure. The blasting process brings the strongest compressive stress into the carbide tools’ subsurface (see fig. 4). Blasting experiments on commercially ground cutting inserts were performed, using blasting pressures of \( p_{bl} = 2, 3 \) and 4 bar. Surface residual stresses between \( \sigma = -1000 \) and -1100 MPa are detected. The depth distributions are very similar, and the impact depth is limited to about 5 µm, independent of the blasting pressure (fig. 5).

Etching Process, Variation of Substrate Voltage. Different etching experiments were performed, changing the substrate voltage between \( U_{sub} = 200 \) and 600 V. Each specimen was etched for 1 hour. At 300 V two different runs were executed with different resulting specimen temperatures of 560° and 190°C, respectively. The surface residual stress values show a correlation to temperature: The low temperature etching process shows the least residual stress reduction, while all others are on about the same level. The total impact depth however is influenced only on a small scale. In a
distance from the surface between 4 and 5 µm no compressive residual stress can be detected any more (fig. 5, C).

Fig. 5: Influence of parameter changes on residual stress impact depth

Summary

Continuous residual stress depth distributions in the PVD-coated carbide tools’ subsurface, consisting of coating and substrate subsurface, can be determined by the application of the scattering vector method. In the upper substrate subsurface there exists a region of tensile residual stress, which endangers the tool cohesive damage in case of additional external tensile load.

During the investigation of the single process steps for the manufacturing of PVD-coated carbide cutting tools, concerning the substrate residual stress, it was found that each of the considered steps is responsible for a characteristic increase or decrease of compressive residual stress. The final PVD-coating process leads to a decrease of compressive stress on the basis of two different mechanisms: a thermal and a mechanical one.

The impact depth of all process steps to the substrate residual stress is restricted to a few micrometers. A variation of parameters of the so far applied processes cannot bring compressive residual stress into greater depths. Changes in axial feed \( v_{fa} \), blasting pressure \( p_{bl} \) and substrate voltage \( U_{sub} \) lead to slightly different residual stress values in the surface, but not to higher impact depths of compressive stress. Etching experiments show that the substrate temperature \( T \) is responsible for compressive stress reduction. The low temperature experiment leads to the least residual stress reduction. The effect on the impact depth, however, is minimal. Additional or alternative process steps have to be found, which have the ability to bring stronger compressive residual stress into greater substrate subsurface depths, in order to avoid cohesive tool damage. Future investigations will investigate effects of parameter changes of the PVD-coating process on the residual stress state of the tool’s overall subsurface.
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References


