Pre PVD-Coating Processes and Their Effect on Substrate Residual Stress in Carbide Cutting Tools

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\textbf{Abstract.} Cohesive damage of PVD-coated cemented carbide cutting tools is ascribed to the residual stress state of the substrate subsurface. The present paper shows the formation of the substrate residual stress in the process chain as well as the stability of the single process steps referred to the scattering of the residual stress values. Depth resolved residual stress measurements across coating and substrate subsurface show a layer in the substrate, where possibly tensile stress occurs, from where cohesive damage may be initialized during tool use. Results of experiments are presented, where the influence of parameter variations in pre coating processes on the residual stress state is investigated. The characteristics of compressive residual substrate stress during the final PVD-process is presented as well as a correlation between coating and substrate stress.

\section*{Introduction}

For nearly 30 years cutting tools are coated with thin films of hard materials, in order to increase tool life. The two most important procedures are physical (PVD) and chemical (CVD) vapour deposition. The trend of coating cutting tools is increasing [1], and the worldwide rise of high speed and high performance cutting processes demands new technologies and an increasing spectrum of layers and layer materials [2,3]. For the development of new tools pre coating processes play an important roll [4,5] as well as post coating processes [6,7,8].

Despite all progress in developing tool coatings, some characteristic damage types still occur: adhesive (flaking of the coating) and cohesive damage (flaking of the coating with adhering substrate material). Especially cohesive damage affects process stability, as the tool fails abruptly and leads to a reduction of productivity and workpiece quality.

The reason for cohesive damage has been assigned to the residual stress state of the unloaded tool [9,13,14]. The formation of residual stresses during the process chain, the residual stress state of the unloaded tool as well as the influence of parameter changes in pre coating processes on residual stress are described in the following.

\section*{Substrate Residual Stress}

PVD-coatings on cutting tools bear high compressive stress, whilst the carbide substrate shows clearly less compressive stress. In order to observe the generation of compressive stress during the process chain, tools have been taken from the manufacturing process after each process step in order to determine the residual stress state. A characteristic distribution could be observed. The very weak compressive stress after sintering is intensified by grinding, and again increased by blasting. Etching reduces compressive stress to about the level after grinding, additionally the PVD-coating process decreases stress slightly [10]. Depending on manufacturer and batch the residual stress levels may differ, but the trend of stress formation during the process chain is always the same.

In order to estimate the scattering of the residual stress after each process step, a large number of residual stress measurements of commercially manufactured carbide indexable inserts, PVD-coated with \textit{(Ti,Al)N}, has been performed. The measurements were carried out by applying the $\sin^2\psi$...
method [11]. Tools of different manufacturers and batches have been investigated. Experimental details of the coating processes specific to the manufacturer are not considered. Residual stresses as a result of manufacturing processes are caused by mechanical and thermal loads. If the mechanical loads are predominant, the result is compressive stress due to plastic deformation. If the thermal loads are predominant, tensile stress is induced due to thermal expansion and subsequent shrinking. In machining processes always both effects occur concurrently. The one with stronger influence determines the character of residual stress in the workpiece. In Fig. 1 the scattering of the measured residual stress values after selected process steps is presented. The residual stress after sintering includes PSTS processes (pressing and sintering to size). The results of all process steps scatter in a wide range (> 400 MPa), but the stress development, as described in [10], still can be traced.

![Diagram of residual stress values](image)

**Fig. 1:** Scattering of residual stress values after selected process steps in tool manufacturing

The residual stress after sintering is a result of thermal and mechanical conditions during the sintering process. Grinding is performed using a coolant, so that it can be assumed that mechanical loads predominate, which shifts residual stress into compressive direction. Blasting is a process nearly without thermal load. It shifts residual stress even more into the compressive range. Etching removes the cobalt binding material, leading to a release of the WC grains, which causes a decrease of compressive stress. This effect is supported by the high temperatures during etching. The concluding coating process is also performed at high temperatures, which leads to a shift of residual stress into tensile direction.

**Depth Resolved Residual Stress**

The results obtained by the application of the $\sin^2\psi$ method cannot explain the occurrence of cohesive damage due to residual stress, as all coated tools bear compressive stress in their substrate subsurface. Additional investigations with the scattering vector method were performed. This method allows for depth resolved residual stress measurements by decreasing the maximum penetration depth of the X-rays on a geometrical way [12]. For this a special 5-circle goniometer is required. These investigations located a zone with tensile residual stress in the substrate below the...
interface. Additional external tensile loads, as they may occur during the cutting process, may lead to cohesive substrate damage as a result of too high tensile stress in this zone. Fig. 2 shows an obtained residual stress depth distribution of coating and substrate subsurface [10,13]. Due to roughness effects results directly from the surface and the interface cannot be gained.

**Influence of Process Parameter Variation on Substrate Stress Distribution**

The penetration depth of the X-rays into the substrate material is not sufficient for the determination of the depth effect of the process steps on residual stress, due to the high absorption coefficient of tungsten in the cemented carbide. Hence, gradually material removing by electrolytical polishing and \( \sin^2 \psi \) residual stress determinations were performed. It was found that the total depth effect is no more than 5-6 µm. In order to avoid tensile residual stress in the unloaded tool, the intention of the pre coating processes has to be an induction of stronger compressive stress than so far and a greater depth effect. It was investigated, whether a simple parameter variation of the applied pre coating processes can provide these effects.

For that purpose the following parameter variations were conducted: during grinding the axial feed \( v_{fa} \) in a range between \( v_{fa} = 2 - 20 \) mm/min, during blasting the blasting pressure \( p_{bl} \) in a range between \( p_{bl} = 2 - 4 \) bar, and during etching the substrate voltage \( U_{sub} \) in a range between \( U_{sub} = 200 - 600 \) V. The determined residual stress depth distributions show, that neither the variation of the axial feed nor of the blasting pressure were able to induce significantly stronger compressive stress or greater depth effects into the tool’s subsurface. Also the variation of the substrate voltage showed no notable effect. An additional experiment, however, of etching with 300 V at explicitly lower temperatures (190°C) showed, that the compressive stress reduction in this case was clearly diminished in consequence of the lower thermal load. All results of these experiments are presented in Fig. 3 [13].
Influence of the PVD-Coating Process on Substrate Stress

As shown in Fig. 1 there is a reduction of compressive residual stress in the substrate during the PVD-coating process. In order to understand the reasons for this reduction, some of the tools to be coated were masked by enwrapping them in a thin foil of stainless steel. These masked tools together with unmasked ones were put into a PVD-coating system and underwent a coating process. All of them receive the same thermal conditions, but only the unmasked ones are coated. After this experiment the coated tools show a compressive stress reduction of more than 20%, while the masked ones only show a reduction of 10% [13] (Fig. 4). After a chemical decoating of some tools a slight increase of the substrate compressive stress could be detected [14]. The PVD-coating itself obviously is responsible for a partial reduction of the substrate compressive stress. The rest of the reduction is caused by thermal effects, as the experiments with the masked tools proved.

Fig. 4: Substrate stress reduction during PVD-coating process

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**Fig. 3: Influence of parameter changes on residual stress depth effect**

**Fig. 4: Substrate stress reduction during PVD-coating process**
As a participation of the coating in substrate stress reduction could be proven, it was investigated whether the magnitude of the coating stress has a detectable influence on the substrate stress. For this from all investigated batches three have been selected exemplarily, which show quite an expanded stray area of the coating stresses. This includes one batch, where no tool rotation during PVD-coating was applied, in order to get flank faces with very high and very low compressive stress, respectively. The analyses of the results show, despite the high stray area of the values, that there is a correlation between coating and substrate stress: The higher the coating compressive residual stress, the smaller the compressive stress in the substrate (Fig. 5). As the sum of all stresses in a specimen is equal zero, a higher coating compressive residual stress must be compensated by a compressive stress reduction in the substrate. Thus the correlation of coating and substrate stress may be explained by a compensation effect, which results in a shift of stress in the subsurface into tensile direction.

![Fig. 5: Correlation between coating stress and substrate stress](image)

**Summary**

The sporadically occurring cohesive damage of PVD-coated carbide cutting tools can be assigned to a critical damage zone in case of additional external tensile load, which lies in the substrate subsurface and possesses tensile residual stress. The residual stress state in consequence of machining is a result of different consecutive pre coating processes. The depth effect is limited to a few microns only. Due to thermal effects and compensation of the high compressive coating stress, the substrate compressive stress is reduced during the generally final PVD-coating process. Intention of the pre coating processes has to be a stronger compressive substrate stress and a greater depth effect. This objective cannot be achieved by a simple parameter variation of the usual pre coating processes, just etching at lower temperatures shows less compressive stress reduction. A correlation of coating stress and substrate stress was found. Suitable pre coating processes as well as a fitting ratio of coating and substrate stresses have to be found, in order to minimize the risk of cohesive tool damage.
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References


