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RESEARCH

Residual Stress Distribution in PVD-Coated Carbide Cutting Tools – Origin of Cohesive Damage

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A B S T R A C T

PVD-coatings for cutting tools mean a substantial progress for tool lifetime and cutting conditions. Such tools, however, hold the risk of cost intensive sudden process breaks as a result of cohesive damage. This damage mechanism does not consist of a coating adhesion problem, but it can be traced back to the residual stress distribution in coating and substrate. This paper shows how residual stresses develop during the process chain for the manufacturing of PVD-coated carbide cutting tools. By means of different methods for residual stress determination it is shown that the distribution of residual stresses within the tool finally is responsible for the risk of cohesive tool damage.

1. INTRODUCTION

The presentation of carbide cutting tools at the Leipzig Spring Fair in 1927 was a milestone in the development of cutting materials, and finally led to the design of new, powerful machine tools [1,2]. A comparable progress was achieved by the coating of cutting tools with thin hard material films, which is applied since the 1960s. The two most important procedures for it are PVD (physical vapour deposition) and CVD (chemical vapour deposition) methods. The compound as a result of tool coating means a properties improvement, which cannot be reached by any of the materials on their own. The business trend of coating is increasing [3].

Besides abrasive wear coated cutting tools show two typical kinds of damage: adhesive and cohesive. Adhesive damage is a result of lacking coating adhesion, which may lead to a flaking off of the coating during the cutting process. As a consequence, abrasive tool wear is strongly accelerated. In the case of cohesive damage, however, the bond between coating and substrate is stronger than the substrate itself. Hence, the coating with adhering substrate material flakes off. In this case the process has to be interrupted immediately in order to prevent workpiece damage. Cohesive damage can be traced back to a weakening of the substrate material. The reasons for this weakening can be found in the presence of too low compressive residual stress in the substrate's subsurface, as assumed by Friemuth [4]. In the following it will be shown, by which methods residual stresses of coating and substrate can be determined, and how the reasons for cohesive damage can be deduced from that. The results of these investigations have been presented orally at a conference in October 2011 [5].

2. RESIDUAL STRESS

Compressive residual stresses have an extending effect on lifetime [6-8], as load induced stresses superimpose residual stresses. For PVD-coated cutting tools it could be shown by means of X-ray diffraction that the coatings possess strong, while the substrates show moderate compressive residual stresses [9]. Recent investigations show, that the compressive stress in coatings can be increased considerably by post-coating blasting processes [10]. Only the application of special X-ray techniques however may deliver information on the local distribution of residual stress, as will be exemplified in the following.

2.1 Methods of residual stress determination

In order to understand the correlation between residual stress and cohesive damage, geometrically simple carbide cutting inserts of the geometry SEKR1204AFN-MS from the carbide type THM have been characterized by X-ray diffraction methods concerning their coating and substrate residual stresses. Commercially available tools of different manufacturers, PVD-coated with approximately 3 μm (Ti,Al)N, have been investigated. The universal sin$^2\psi$-method served as standard procedure. With this method, lattice strains within the volume that is penetrated by the X-ray beam, are measured [11]. The method provides good approximations of the residual stress states of coating and substrate, though information on the depth distribution thus is not obtained. The results of sin$^2\psi$ analyses given here must be interpreted approximately as mean values from the whole irradiated material volume. During one single measurement the penetration depth of the X-rays varies as a result of changing inclination angles ψ. Therefore, one of the preconditions for the applicability of the sin$^2\psi$-method is, that within the penetration depth of the X-rays of a few μm, there are no strong residual stress gradients. This precondition is not fulfilled for the tools investigated here. For this reason, additionally a special method has been applied, which provides depth resolved information. The procedure is the scattering vector method, developed by Genzel [12], performing a continuous reduction of the X-ray penetration depth in a geometrical way to the point of zero (Fig. 1).

For measurements applying the scattering vector method, a special 5-axes diffractometer is required, which allows a rotation of the specimen in reflection position around the scattering vector $g_{\phi\psi}$. By this the angle between the primary beam (PS) and the specimen surface is varied, which changes the X-ray penetration depth.

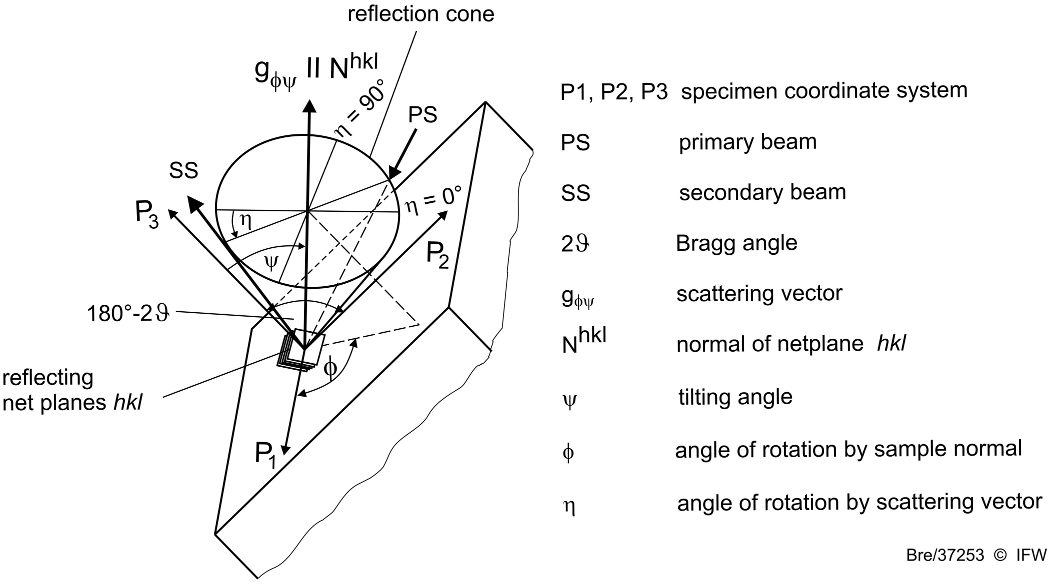

Fig. 1. Principle of the scattering vector method.

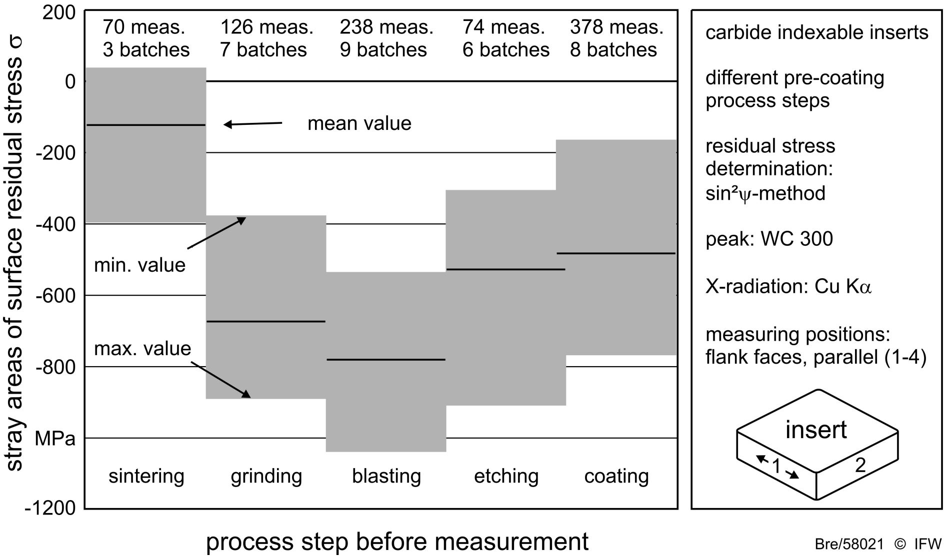

Fig. 2. Typical development of substrate residual stress within the process chain.

Both methods described deliver integral information from the irradiated material volume, and only the scattering vector method gives depth resolved information. The local resolution of both methods is determined by the irradiated area in the specimen surface. In the experiments performed here, the X-ray beam has been defined by a collimator with a diameter of 2 mm. A reduction of the beam diameter is possible in order to increase the local resolution, but the intensity of the diffracted beam would become that small, that the measurement time would increase not acceptably.

In order to have adequate intensity and high local resolution a third method for measurement was applied. It uses synchrotron radiation in combination with a locally resolving microchannel plate as collimator in front of an image plate detector, the so called MAXIM detector [13]. With this equipment sin$^2\psi$-measurements of coating and substrate were performed. The PVD-coated tools have been characterized concerning residual stresses by all three methods.

2.2 Development of substrate residual stress during process chain

As the tool substrates show moderate compressive stress after coating, which is not as distinct in this way after sintering, it stands to reason that certain process steps in the production of coated carbide tools are responsible for the generation of compressive stress. In order to investigate this generation during the currently applied process chain, a great number of tools have been taken out of the process chain after different process steps from three different tool suppliers. Two of them used AIP (arc ion plating), the third one applied MSIP (magnetron sputter ion plating) for coating. Recently alternative process steps are investigated, e.g. substrate pre-coating treatments like abrasive flow machining and laser ablation technologies [14].

For the investigations described in the following, residual stress was determined at the flank faces of tools from different batches applying the sin2ψ-method. Fig. 2 shows the results of these investigations along with mean values and stray areas [15]. Firstly, it is noticeable that the values after all process steps stray in an area of about 400 MPa, all values of the coated tools however are compressive. Overall considered, the residual stress values did not show a systematic dependency from the applied PVD-technique. The composition of the (Ti,Al)N coatings was all about the same. The residual stress values after the different process steps were not specific to a certain supplier.

After sintering the specimens initially show no or few compressive stress. Grinding induces compressive stress, which is augmented by the blasting process. Etching reduces compressive stress to about the level after grinding. The PVD-coating process itself leads to another reduction of the compressive stress in the substrate.

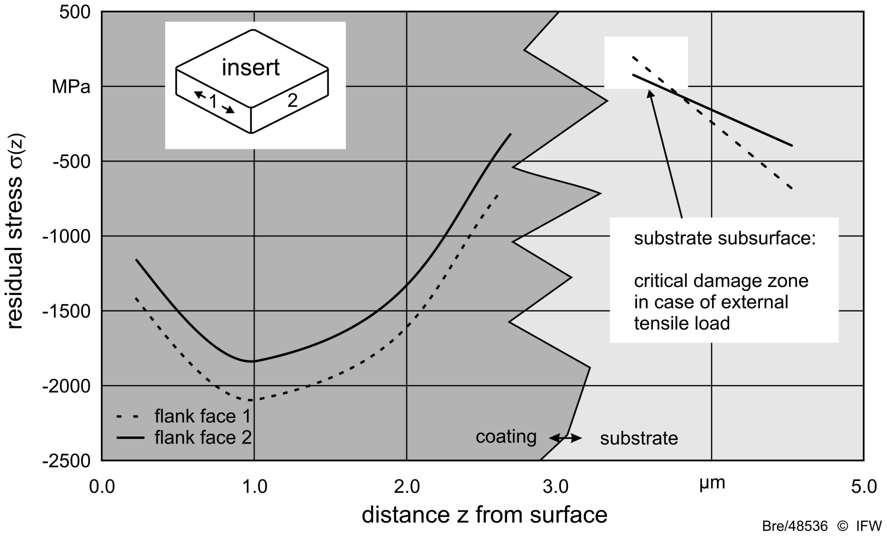

Fig. 3. Typical residual stress depth distribution in coating and substrate.

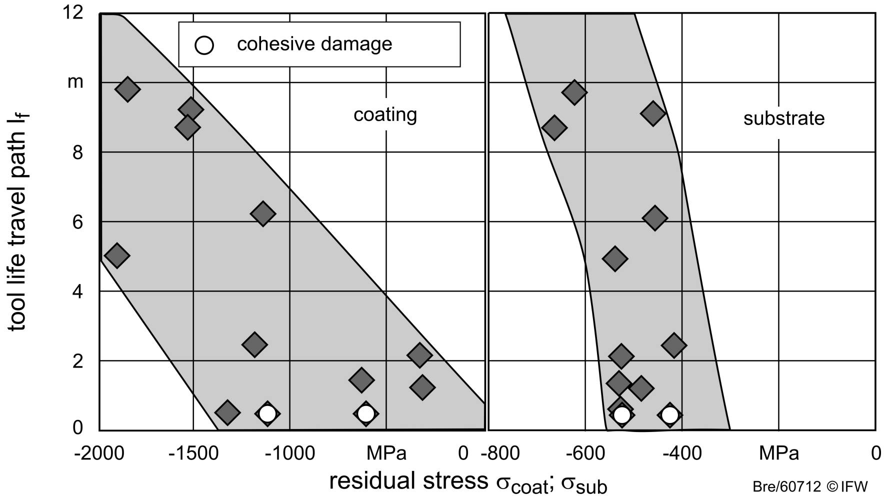

Fig. 4. Tool path depending on coating and substrate residual stress.

2.3 Depth resolved residual stresses in coating and substrate

As the sin$^2\psi$ measurements do not give information on the residual stress depth distribution, depth resolved measurements of coating and substrate have been performed applying the scattering vector method. Using Co Kα radiation a maximum information depth of about 3 µm can be achieved in the coating material (Ti,Al)N, and about 1.5 µm in the substrate material WC with 6% Co. A typical residual stress depth distribution in coating and substrate is shown in Fig. 3 [16].

Directly in the surface and in the interface area no reliable data can be obtained as a result of surface roughness effects. It can be observed that the coating possesses a distinct compressive stress maximum in about 1 µm depth. In direction to the interface the compressive stress decreases. The substrate material shows moderate compressive stress with a steep gradient in direction to the interface. As a result of this tensile stress in the substrate subsurface of the unloaded tool may occur. During tool use in case of additional external tensile loads a critical stress value for the substrate material may be exceeded, the material failures, and cohesive damage appears.

3. CUTTING TESTS

In order to verify, that the stress state in the substrate's subsurface forwards cohesive tool damage, cutting tests with selected tools from all three suppliers have been performed. C45 has been cut by single tooth face plain milling. The cutting conditions were as follows: tool diameter d = 80 mm, cutting speed v_c = 250 m/min, depth of cut a_p = 2 mm, width of cut a_e = 32 mm, feed per tooth f_z = 0.3 mm. The stop criterion was VB = 200 μm.

Before performing the experiments, residual stresses of coating and substrate have been determined applying the $\sin^2\psi$-method. According to the state of knowledge those tools, showing the lowest compressive substrate residual stress, should tend to cohesive damage. The analysis of the results firstly showed, that coating stress has a major influence on tool lifetime, which agrees very well with the results obtained by Klocke et al. [17]. Stronger compressive stress in the coating increases tool lifetime (Fig. 4, left). Also stronger compressive stress in the substrate has a positive effect on tool life (Fig. 4, right). This set of experiments shows that cohesive damage occurs suddenly after starting the experiment. According to this it is not a result of tool wear, but obviously in fact caused by too low compressive residual stress in the substrate. Indeed cohesive damage did not occur, as expected, at all tools with lowest substrate compressive stress (Fig. 4).

4. LOCALLY RESOLVED RESIDUAL STRESS

In order to understand why cohesive damage does not occur at all tools with low compressive substrate residual stress, the local distribution of coating and substrate stress after PVD deposition is investigated. For this purpose synchrotron radiation and the MAXIM detector in combination with the $\sin^2\psi$-method are applied. The locally resolved stress measurements of the coating as well as of the substrate show very inhomogeneous distributions. In Figs. 5 and 6 the residual stress distributions in the flank face are shown.

These distributions deliver the key of understanding the appearance of cohesive damage. As a result of the inhomogeneous distribution of residual stress there are regions of the tool with different grades of “endangering”. In Fig. 5 it can be observed that cohesive damage of the left tool corner is more probable than of the right one. These local stress differences cannot be detected by methods in the X-ray lab, as $\sin^2\psi$ and scattering vector method both cannot deliver such local resolution. The reasons for the non-uniform stress distribution are under further investigation. Another characteristic can be seen in Figs. 5 and 6. At those positions, where the compressive stress of the coating shows maxima, substrate compressive stress is least. This indicates that coating stress has an influence on substrate stress. This finding confirms the observance that there is a trend to decreasing substrate stress at increasing coating stress (Fig. 7) [18].

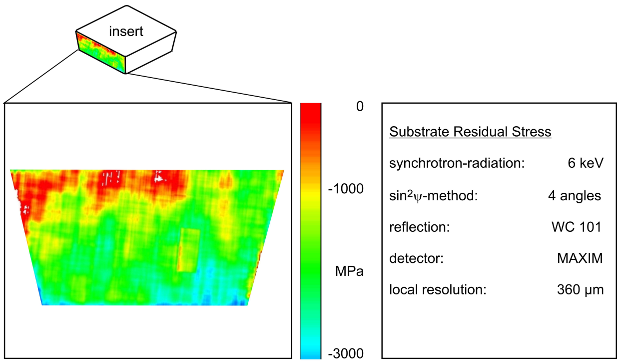

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Fig. 5. Locally resolved substrate residual stress.

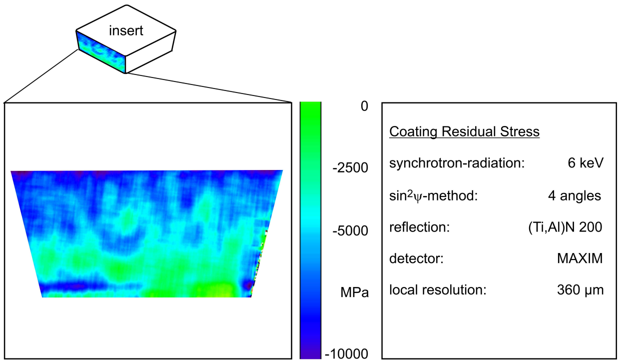

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Fig. 6. Locally resolved coating residual stress.

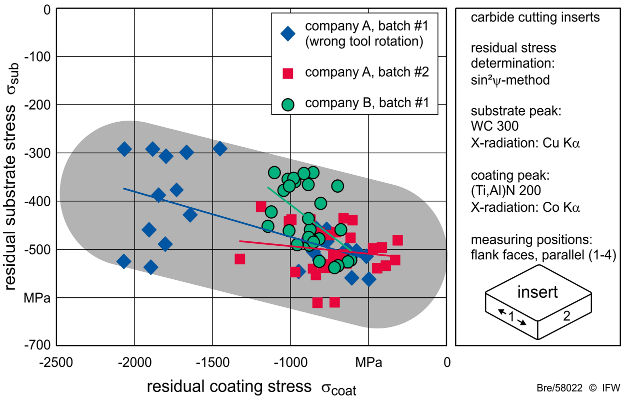

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Fig. 7. Residual coating stress influencing residual substrate stress.

5. MODEL FOR STRESS DEVELOPMENT

The obtained results from these investigations offer the understanding of residual stress generation in the substrate subsurface and enable an expansion of the conception for the reasons for cohesive damage based upon residual stress [4]. The coaction of thermal and mechanical loads during the succeeding process steps for tool manufacturing is responsible for the final residual stress state of the tool. As a rule mechanical loads cause compressive stress, while thermal loads cause tensile stress. In special cases also mechanical reasons can lead to a shift of the residual stress level in direction to tensile stress. This will be explained in the following when discussing the contributions of single process steps to the development of residual stress (Fig. 8).

During the sintering process high thermal and mechanical loads exist. The effects concerning residual stress however cancel each other, so that the surface near region of the tools has no or only few compressive residual stress. During grinding mechanical and thermal loads are present. Mechanical loads shift the residual stress level into the direction of compression. The contrarily acting thermal load is widely suppressed by the coolant. This results in another shift of the residual stress into the direction of compression. The impact, however, can only be detected in depths near the surface (z < 10 µm). In greater depths slight tensile stress may occur as a result of compensation of compressive stress. The subsequent blasting process shifts the stress level again in the direction of compression by its mechanical loads. Thermal effects do not exist here. The compressive stress level after blasting is the strongest during the whole process chain. Indeed it is also limited to small depths (z < 10 µm). In greater depths also tensile stress may exist for compensation reasons.

During etching the thermal effect of the process dominates (T > 500°C). By this the stress level is shifted into tensile direction. This tendency is supported by a mechanical effect: By a stronger setting back of the Co binder, the WC grains are relieved mechanically, which additionally shifts the stress level into tensile direction. The stress state after etching corresponds approximately to that after grinding.

During the PVD-coating process also the thermal effect dominates (T ≈ 500°C), which leads to another shift into tensile direction. Also here the thermal effect is supported by a mechanical effect: The stronger coating compressive stresses are compensated in the substrate's subsurface by an additional shift into tensile direction.

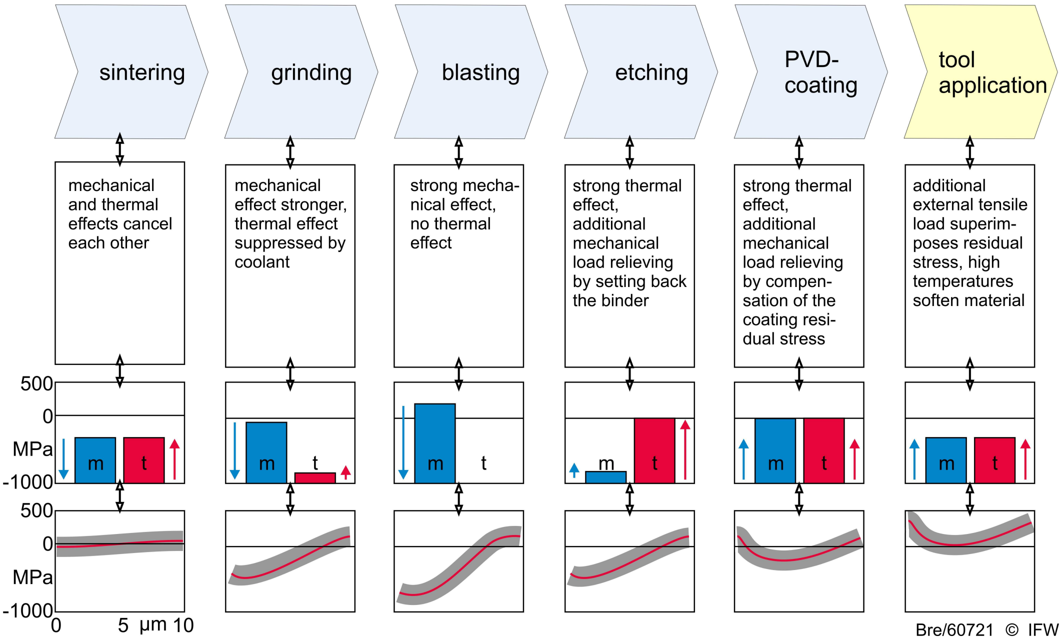

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Fig. 8. Empirical model for the generation of residual stress in the substrate as origin for cohesive tool damage.

The completed tools possess surface near regions with no or even tensile residual stress. During tool use additional tensile loads occur, which superimpose the residual stress. This may lead to another shift of the stress level into tensile direction. The material, which is furthermore softened by the high temperatures, fails more easily. During usage local exceedings of critical tensile stress values may occur, which, potentially supported by micro cracks, are responsible for the appearance of cohesive damage. By the unexpectedly inhomogenuous residual stress distribution it is difficult to predict cohesive damage based upon X-ray diffractometric stress determinations reliably.

6. SUMMARY AND OUTLOOK

Cohesive damage of PVD-coated cutting tools, i. e. flaking off of coating with adhering substrate material, means a problem for process safety. Cohesive damage is not a wear effect, but it suddenly occurs after process start. It can be traced back to a disadvantageous distribution of residual stress in the substrate material. It could be shown that in an unloaded cutting tool there are regions in the substrate's subsurface, where tensile residual stress may exist. An empirical model for the development of the final residual stress state of the tool was generated. The existence of strongly inhomogeneous residual stresses hinders a reliable prognosis for the appearance of cohesive damage. In additional investigations the reasons for the stress inhomogenities and how they can be countered, must be found out. Furthermore, processes have to be found, which enable stronger compressive residual stress in the substrate's subsurface, and a shifting into greater depths. A variation of parameters at currently applied processes has been investigated, but did not lead to noteworthy improvements [15,18].

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