Finite element shot peening simulation of coated cutting inserts

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Abstract

In the machining industry, coated hard metal cutting tools are exposed to extreme conditions in terms of thermo-mechanical loading, so tailored resistance to such loading is required. A possible method to extend their life is to introduce compressive residual stresses in the coating and/or substrate by a shot peening process. The work aims to predict the influence of blasting parameters on the development of residual stresses distributions in coated WC/Co inserts. The investigated coating consists of a TiCN and an Al_2O_3 layer. The relevant industrial parameters which were taken into account are particles speed, impact angle and diameter. The work will provide practical guidelines for a process optimization as well as guidelines to prevent damage in the tool by choosing wrong process parameters.

Introduction

Replaceable tips for metal cutting are called indexable inserts and they are commonly coated by different types of coating materials in order to extend their service life due to increased wear resistivity. A further improvement of these inserts is expected from a shot peening process, by which small edgy or globular particles impact on the tool's surface and introduce into its structure compressive stresses. The compressive stresses shall close micro cracks, thus boosts the tool's performance.

According to Broszeit et al.[1] the residual stresses during the shot peening are developed by two phenomena. First is the Herzian contact pressure causing the residual stresses occur near the surface. Second is the plastic stretching of the surface layer by multiple impacts, which produces the maximum residual stresses at the surface. Schiffner et al. [2] found out that adjacent impacts decrease the residual stresses in the area of the first impact and increase them in the area of the second impact. Different residual stresses developed by consecutive and simultaneous impacts was found in the work from Schwarzer et al. [3]. However, the location of the maximum residual stresses was strongly influenced by shot peening parameters and the amount of residual stresses was changed only slightly. Increasing residual stresses with increasing shots diameter and impact speed were observed in the work of Mylonas and Labeas [4]. G. H. Majzoobi et al. [5] found that by exceeding a certain shot peening speed, the residual stresses are not raised anymore. It was also proved that after a sufficient number of shots, the residual stresses near the surface get the same everywhere. Simulation from Tkadletz et al. [6] showed that surface roughness plays significant role in the forming of the plastic strain. A 3D shot peening simulation including 134 shots impacting randomly was performed by Bagherifard et al. [7]. A slight non uniformity in the residual stress deployment and deformation was observed. The roughness presence on the probe was found as a reason for slight result differences between simulation and measurement. By increasing the treatment time, a notable change of results was not observed. Taehyung Kim et al. [8] showed that after a few cycles of repeating an impact pattern, it does not matter in which order the particles impact; the residual stress distribution is very similar. Increasing uniform deployment of residual stresses and plastic strain with increasing number of impacts was found in the work of X. Kang et al. [9]. According to [8], the impact angle smaller than 45° has only a weak peening effect leading to small dimples, consequently small induced stresses and plastification.

All calculations in the presented work are conducted by means of finite element method (FEM) using ABAQUS 6.14.2/Explicit. At the beginning of the work, the results of 2D and 3D one ball impact simulation were compared to justify the 2D approach. A 2D plane strain finite element model is developed describing the impact of multiple elastic globular particles on the tool with elastic-plastic material behaviour. Simulations are conducted with varied parameters such as particles diameter, speed, and impact angle. As main result, the influence of particle size, speed and impact angle on horizontal residual stresses and plastification near the surface is calculated and residual stress profiles are shown.

1. Comparison of 3D and 2D analysis

A 2D finite element approach is used as substitution for time consuming 3D analyses. However calculating of 3D problems using 2D models is very advantageous in terms of computational time, the 2D calculation ignores the third dimension and misses some aspects of the real problem. For instance assuming a plane strain problem a cylinder impact instead of a ball impact is calculated. Then, the contact area at the tool surface is rectangular and the mass is distributed uniformly along the cylinder's axis. Therefore, a 3D study was made to calculate the possible error range using a 2D blasting model.

1.1. Model and material data

The substrate coated by TiCN as base and Al_2O_3 as top layer is peened by one spherical particle of Ø250μm with a speed of 300m/s and an impact angle of 90°. The friction coefficient between particle and surface is assumed 0.5. The sketch of the 3D- and 2D- simulation is depicted in Figure 1. In the 3D simulation, one quarter of the model with corresponding symmetry boundary conditions is considered. The target is represented by a cube of 5x5x5mm whose upper face is covered by the two coating layers, both 8.6 μm thick. Substrate and coatings are tied together. The sides and the bottom of the model are fixed. In order to achieve the appropriate discretisation, the mesh is graded in the impact area so that the smallest elements are placed in the middle of the target, where the balls impact. The assumed contact area of the sphere is meshed accordingly. The total number of elements is 526378. The model uses C3D8R elements for substrate and layers and C3D10M elements for the impacting particle. The 2D model uses plane strain elements for the calculation. The target size is 10x5mm. On its surface are two 8.6μm thick layers representing the coating. The target is meshed by 818000 CPE4R elements. The particle is modelled as full circle, containing 4137 CPE4R and CPE3 elements. Sides and bottom of the model are fixed. A tie constrain is used between the TiCN layer elements and Al_2O_3 and substrate elements. Materials used for the tool insert are modelled with elasto-plastic behaviour. The substrate material is a hard metal consisting of 6 wt. % Co, 2wt. % mixed carbides and 92% tungsten carbides (WC) and has a Young's modulus of 617GPa, a Poisson's ratio of 0.22, a density of 14950kg/m^3, and a Yield stress of 1850MPa with non-linear hardening up to 5750MPa at a plastic strain of 0.015. The material properties for aluminium oxide (Al_2O_3) and titanium carbo-nitride (TiCN) are acquired from a previous project and [6]. As shot peening material a 62% ZrO_2, 28% SiO_2, 5% Al_2O_3 mixture with elastic behaviour taken from [6] is used.

1.2. Results of the comparison

The blasting results compared in Figure 2 are the equivalent accumulated plastic strain (PEEQ), and residual stresses in horizontal direction (S11). The main task of this comparison is to compare the distribution of plastification and stresses between 2D and 3D simulation and their maxima. The results will provide an information about the relation of 2D and 3D calculations.

The comparison proved that the distribution of PEEQ and S11 calculated by 3D and 2D approach is similar. The highest amount of plastification in both cases occurs in the substrate directly under the impact area, whereas a lower plastification is observed in the upper part of the Al_2O_3 layer.

In comparison to 3D analyses, the 2D simulations generally evince lower maximum of plastification and stresses. The maximum PEEQ values are by 57% smaller in the 2D case. In both analyses, the highest S11 residual tensile stresses occur in the TiCN layer and in the transition between the deformed and the even surface of Al_2O_3. The highest compressive stresses are calculated in the particle impact area at the surface and in the transition between deformed and even surface at the bottom of the TICN layer. The maximum tensile stresses differ by 24%, the maximum compressive stresses by 17%.

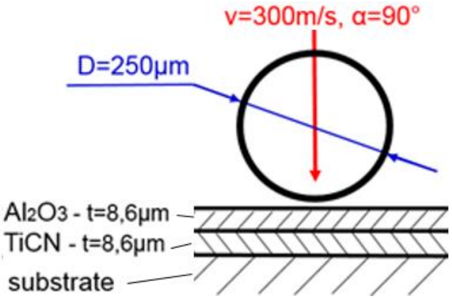

Figure 1 - Sketch of the 3D and 2D one ball impact model

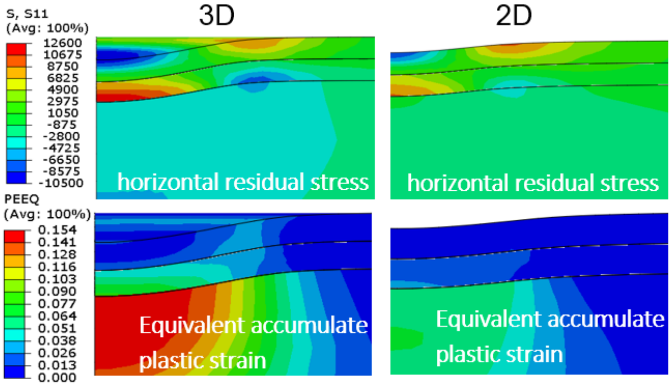

Figure 2 - 3D-2D comparison of one ball impact; horizontal residual stresses [MPa], equivalent accumulated plastic strains [-]

2. Multiple shot peening

The aim of the 2D multiple shot peening simulation is to find how the parameters of the blasting process influence the level and distribution of the resulting residual stresses. From the 2D-3D study it can be concluded that for obtaining quantitative correct results 3D simulations are necessary, however, for evaluating the influence of parameters a 2D simulation seems to be sufficient.

2.1. Model and material data

The modelled substrate sized 10x5mm is on its top covered by a TiCN and an Al_2O_3 layer, each 8.6 µm thick, see Figure 3 and *4*. In total 60 spherical particles are shot on the tool. The layers and the substrate are modelled as one part that is divided into partitions to which the corresponding materials are assigned. The balls are arranged in 10 rows with 6 balls in each row. The particles in the same row impact on the surface in the same time. In further impacts of the next rows the balls are placed in that way that the impact spots are shifted by 1/10th of the particle diameter from the previous row. Consecutive rows touch the target surface with a small time interval between the impacts. There is zero distance between particles in the same row. The friction coefficient between particle and surface is assumed with 0.5. All materials used in the multiple shot peening simulation are same like in chapter 1.1. The combination of shot peening parameters, which are used for this study are a diameter of Ø150µm with variable speed of 100ms^{-1}, 150ms^{-1}, 200ms^{-1} and constant speed v=150ms^{-1} with diameters of Ø100µm, 150µm, 200µm. All cases are calculated for the impact

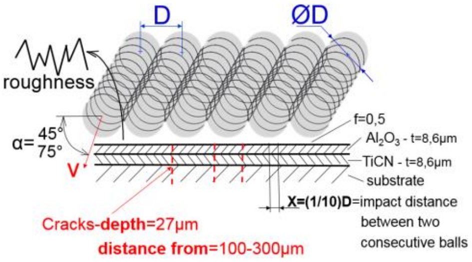

Figure 3-Multiple impact simulation

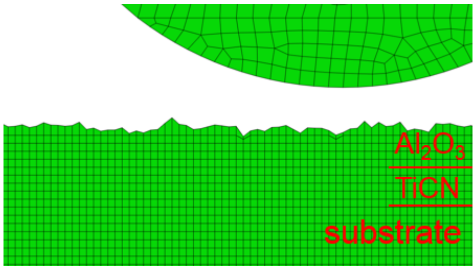

Figure 4-Detailed view of finite element model

angles 45° and 75°. To have model close to reality pre-existed cracks from the coating process, which are 27µm deep and go through both layers and end in the substrate, were considered. The measured and modelled distance between cracks ranges from 100 to 300µm. A real measured roughness of the coatings was used in the model. The model also includes the residual stress state which is measured in the tool before blasting. The measurements were conducted in a previous project. After each simulation, a static calculation was conducted to remove elastic stress waves caused by the particle impact. For comparison also a case without rough coating is calculated.

2.2. Results of multiple shot peening

The comparison between simulation with and without roughness shows a large difference in the maximums of the equivalent plastic strain (PEEQ) and the horizontal residual stresses (S11) distribution, see Figure 5. The coating roughness causes a large plastification of the surface and slightly decreases the plastification depth. Stress peaks at the surface occur due to roughness. Figure 6 shows how varied particles diameter and impact speed influence the plastification and horizontal residual stresses. The results are presented for constant diameter and variable speed (row 1 and 3), and for constant speed and variable diameter (row 2 and 4). The impact angle is in all shown cases 45°. For the smallest impact energies, the plastification occurs mainly at the surface. The higher the impact energy is, the higher the plastification gets and the further it reaches into the depth. In the cases of Ø150µm, 200ms^{-1} and Ø200µm, 150ms^{-1}, a large amount of plastification occurs also in the substrate. In the substrate, the compressive stresses increases with higher speed or bigger particles. The TiCN layer stays for smaller impact energies in the tensile mode, a compression state occurs only for the case of Ø150µm, 200ms^{-1}. The Al_2O_3 layer comes partly in compression and partly in tension. The only case in which the Al_2O_3 layer is complete in a compression state is the case of Ø150µm, 200ms^{-1}. From the comparison in Figure 6 it is evident that the diameter and impact angle have a similar effect on plastification and residual stresses. The horizontal residual stress profiles for a given diameter of 150µm, varied speed and an impact angle of 45° is shown in Figure 7. All values are averaged over 100µm to exclude local fluctuations and to allow a comparison with residual stress measurements which average the stresses over the same distance. The graph also depicts the standard deviation for each averaged value. The influence of the impact angle is shown in Figure 8 for the 150ms^{-1}, 100µm case. It is observed that a steeper impact angle pushes the residual stresses in direction or into the compressive area. Figure *9* shows the comparison of the simulation case of 75°, Ø100µm, 150ms^{-1} with the measurement, which was conducted in [6]. The measured specimen was shot peened by a mixture of globular particles in the range of Ø125-250µm. The horizontal residual stresses in Al_2O_3 and TiCN layer were measured. However, only the blasting pressure 1.5 bar is known, the shot peening speed remains unknown. The blasting was applied under 75° for a time of 14s.From the simulated cases, the case of 75°, Ø100µm, 150ms^{-1} corresponds most to the measurement.

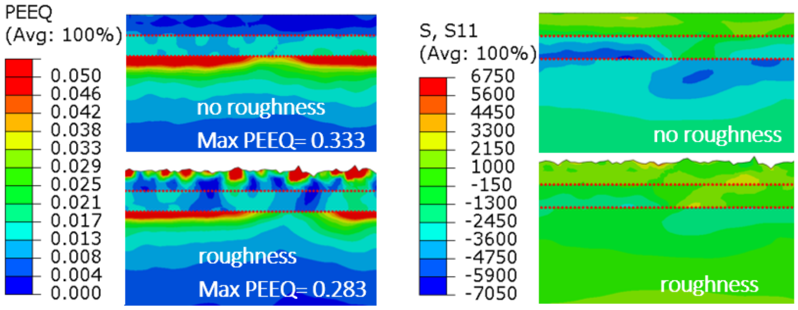

Figure 5- Multiple blasting- equivalent plastic strain (PEEQ [-]) and horizontal residual stresses (S11 [MPa]); comparison; 75°, 200ms^{-1}, 150µm case

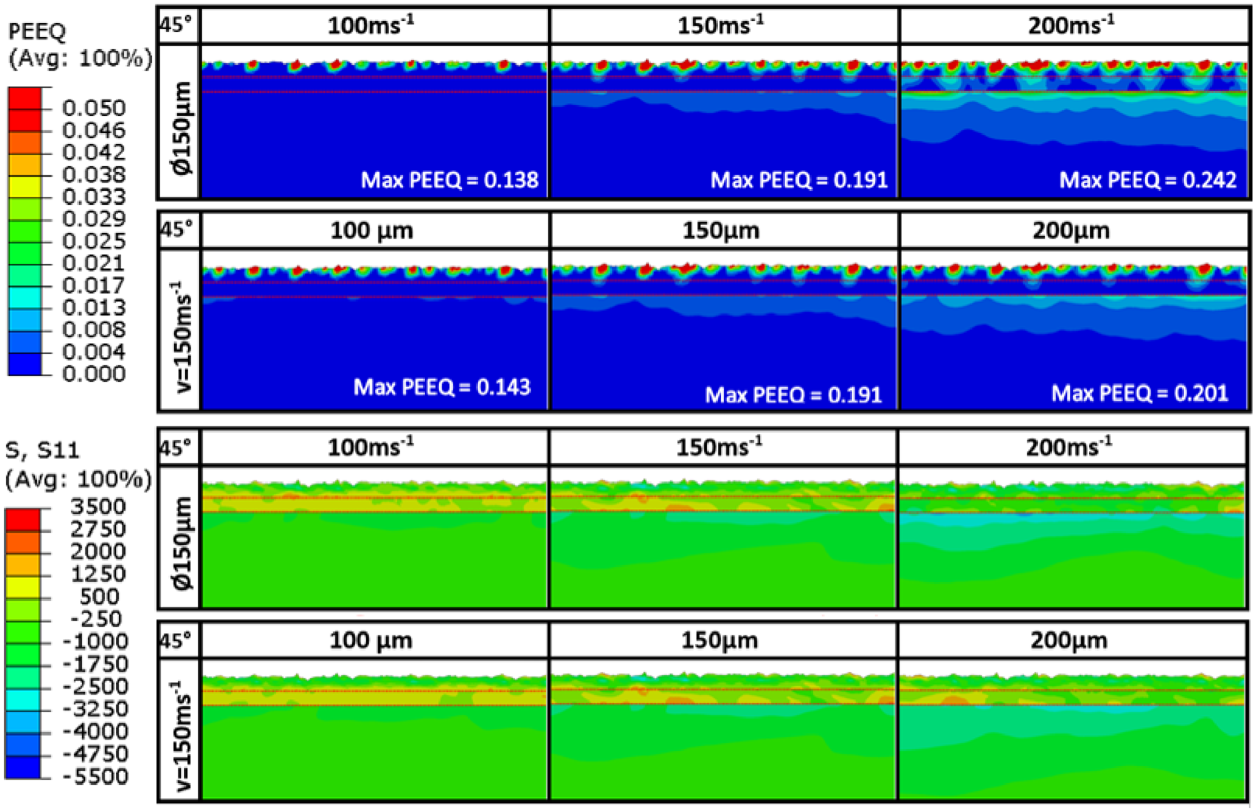

Figure 6-Influence of speed and diameter on equivalent plastic strain (PEEQ [-]) and horizontal residual stresses (S11 [MPa]) after multiple ball impact; impact angle is 45°.

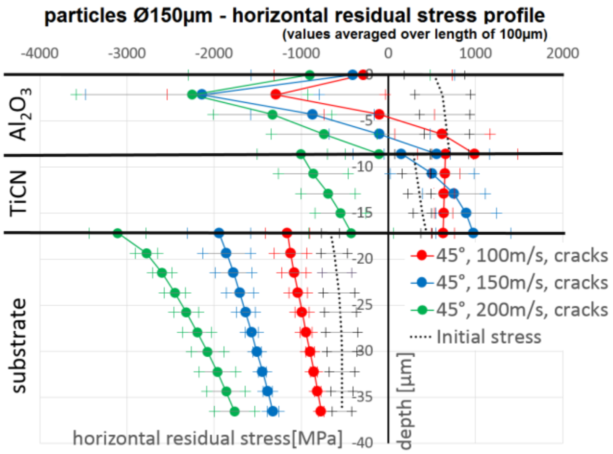

Figure 7-Horizontal residual stress profile comparison

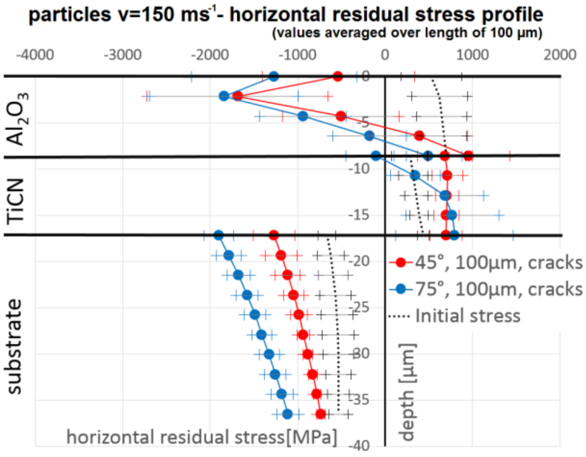

Figure 8-Horizontal residual stress-influence of impact angle

Conclusion

In this work, a 2D multiple shot peening model including coating roughness and pre-existing cracks was created to investigate the influence of shot peening parameters on the horizontal residual stresses and plastification. The investigated parameters are diameter, speed and impact angle. Horizontal residual stress profiles with averaged values to exclude local fluctuations were created. This profiles could be compared to measurements for a similar shot peening process. When the impact energy is sufficient, the residual stresses are moved from a tensile to a compressive state. However, when the impact energy is too low, the residual tensile stresses can be even higher as the initial ones. The comparison of particles with same speed and diameter but different impact angle shows that a steeper angle produces higher compressive horizontal residual stresses. It turned out that the coating's roughness has a crucial influence on the stresses and plastification in the outermost surface layer. The simulations deliver comparable results with similar stresses as obtained by measurements. Especially the calculated depth profile of the stresses is similar to the measurements and shows that the physical process is captured very well.

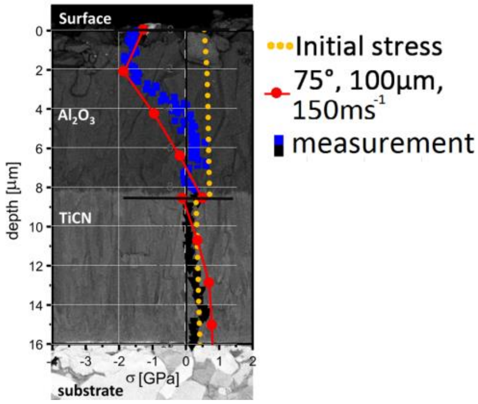

Figure 9-Measurement [6] and simulation comparison of the horizontal residual stresses in the layers

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