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Hard turning of AISI 52100 using PCBN wiper geometry inserts and the resulting surface integrity

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Abstract

To allow for high productivity, high flexibility and avoidance of coolants, hard turning is nowadays an alternative to grinding in the finishing of workpieces in hardened steels. Using wiper PCBN inserts reduces surface roughness compared to machining experiments with conventional inserts at increased feed rate. Although these advantages are known, the effect of wiper PCBN inserts on surface integrity in a hard turning process is not well described in literature. This paper aims at investigating the effect of wiper PCBN inserts on surface integrity and cutting forces in finishing by hard turning of through hardened AISI 52100 (100Cr6) (58-62 HRC). A model based on statistical design of experiments was established to predict cutting forces and surface roughness within a range of cutting parameters. The assessment of surface and subsurface integrity reveals that, when compared to conventional geometry inserts, the application of PCBN wiper inserts leads to significantly improved surface roughness and higher compressive residual stresses.

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Keywords: Hard machining; Turning; Tool geometry

1. Introduction

Finishing by hard turning (HT) represents a distinct alternative to conventional grinding due to a set of advantages such as: higher cost effectiveness, higher productivity, flexible machining and higher material

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removal rate (MRR) [1-3]. As hard turning is usually performed under dry conditions, a positive impact on environmental aspects can be achieved due to the elimination of coolants [2-4].

In order to meet further the requirements for high productivity in the hard turning process, multi-radii (wiper) geometries have been developed lately. These enable to machine parts at higher feed rates without sacrificing on the quality of the machined surface that would be achieved otherwise with conventional geometries at lower feed rates [5-7]. By transferring a small part of the round insert edges into the straight cutting edges of the pointed insert, an insert design adjusted for hard machining producing superior surface finish is achieved. The “wiper radii” are located next to the nose radius and enlarge the contact area of workpiece and tool. The wiper tool geometry has a significant effect on surface integrity and can lead to improvements. The motivation of the present investigation is to assess the effect of wiper PCBN inserts on surface integrity and cutting forces in finishing by hard turning of through hardened AISI 52100 (100Cr6).

2. Material, tool and experimental procedure

The workpiece material employed in the cutting test was through hardened steel AISI 52100 ring specimens (initial wall thickness: 25mm) that were hardened to 60 HRC. The cutting tool material consisted of PCBN inserts (ISO CNGA120408, 60% CBN, 40% TiCN binder). The cutting tests were carried out on a modern 60 kW CNC Lathe. Roughness measurement was performed with a portable perthometer “Mahr M4Pi”. Forces were measured with a dynamometer “Kistler 9121”. An X-Ray diffractometer type “GE XPS 3000” was used to measure the residual stresses. Cr-Kα -radiation and the $\sin^2$psi-method was applied to determine the residual stresses parallel to the cutting direction. 3D Topography measurements were conducted using a WYKO type white light interferometer.

Short time longitudinal turning tests were performed using a defined range of varied cutting parameters (cutting speed, feed rate) and geometries (nose radius, edge radius chamfer angle, insert type). The depth of cut was kept at a constant value of 0.15 mm. Cutting forces were measured simultaneously during the cutting process and surface roughness was measured at regular time intervals after each pass on the machined surface. Additionally, selected cutting conditions were employed to perform tool wear tests in order to compare conventional and wiper inserts and their resulting effect on surface integrity. The parameters are displayed in table 1.

Table 1: Parameter range for the tests

Test	Insert type	Nose Radius (mm)	Edge Radius (µm)	Chamfer Angle (°)	Speed (min^{-1})	Feed (mm)
Short time	Wiper, Conv.	0.4 - 1.2	15 - 35	15 - 35	120 - 180	0.1 – 0.3
Tool wear	Wiper, Conv.	0.8	25	25	150	0.2

3 Results

Based on the data gathered in the short time longitudinal turning tests, a model (for cutting forces and surface roughness) was developed. The model gives information on how significant the effect of the different variables is. Variables without significant effect at 95% level where excluded. The achieved accuracy of prediction was acceptable for cutting forces and surface roughness.

The forces were divided into two independent models: One model regarding the axial force F_a and one for the prediction of the radial and tangential Forces F_r and F_t. When regarding the parameters with significant effect on the cutting forces, it can be stated, that feed has by far the largest effect on the forces leading to an increase in all three cutting dimensions. Using a wiper insert the tangential and radial forces increase, but it has no effect on axial force.
The number of parameters having a significant effect on the surface roughness could be reduced to three: feed, nose radius and insert type. Fig. 1a and 1b show the interaction plot for feed(f) x insert type and nose radius($r_ε$) x insert type respectively. Increasing feed has a great effect on surface roughness. This increment of roughness however, is greater using a conventional insert. Increasing the nose radius leads to better surface finish. Here again the wiper insert is more stable to different nose radii.

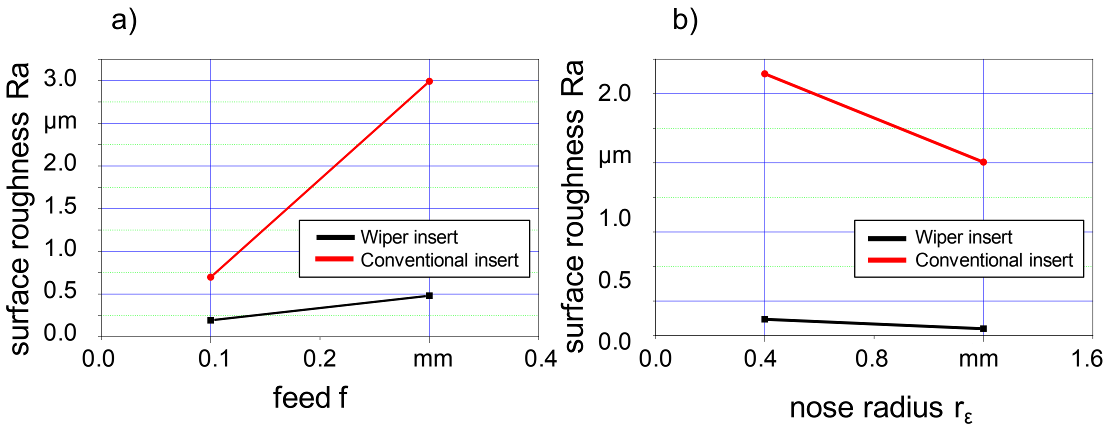

Fig. 1: (a) Interaction Plot: feed(f) x inserts type; (b) Interaction Plot: nose radius($r_ε$) x insert type

Finally it has to be stated that a valid model for surface roughness and cutting forces prediction within the range of parameters was generated. By regarding this model the number of parameters with effect could be cut down significantly. This will make further investigations easier and less complex for example the effect of speed was found to be insignificant for all results and can hereby be excluded from further investigations. The good reproducibility of the results was verified by repeating cutting experiments applying case hardened AISI 1515 (16MnCr5) four times. Fig. 2 presents the nose radius and feed-dependent-roughness in a contour plot. The small marked area (circle) in the surface roughness plot of the standard insert (Fig. 2 a) is commensurate to the total plot of the wiper insert (represented by the line).

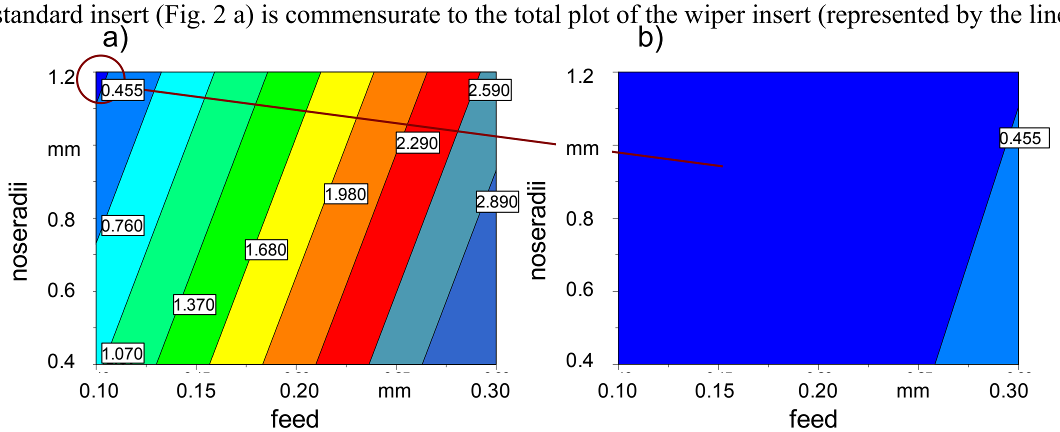

Fig. 2: (a) Contour of Ra for standard insert type; (b) Contour of Ra for wiper insert type

The roughness of the machined surface was also measured as a function of cutting time, thus as a function of tool wear. Regarding Ra (Fig. 3) the surface produced using a wiper insert is superior to the surface produced using an insert with conventional geometry continuously. With increasing tool wear, the surface roughness value resulting from the wiper insert increases, while it decreases with the conventional insert. Both inserts tend to reach a stable value after a specific cutting time. These values are on one hand, regarding wiper insert, $Ra_{stable} \approx 0.5$ µm after about 5 min contact time, on the other hand the conventional insert produces a surface roughness of $Ra_{stable} \approx 1.0$ µm after about 5.5 min contact time.

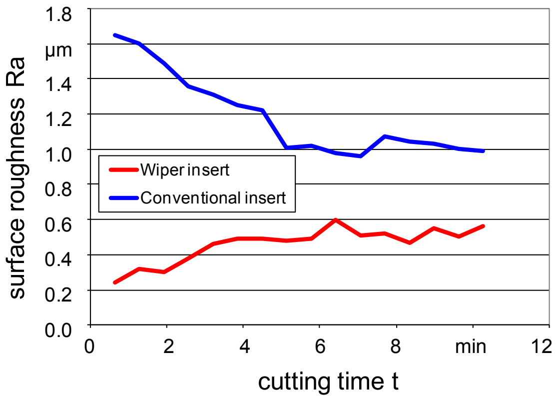

Fig. 3: Ra plotted against contact time

Beside the 2-Dimensional measurements, 3D-topography of surfaces was also measured employing white light interferometry. The surface produced by the wiper insert is smoother at all settings (Fig. 4, note that for better clarity the scale in the vertical axis is not the same). By comparing the surface topography resulting from cutting experiments with new and worn inserts, it becomes obvious that the new insert produces a more uniform surface, while the surface produced using the worn insert shows areas influenced by for example temperature and friction. Subsequent to the assessment of the 3D-topography, roughness parameters were extracted from three measurements in a 50x50 µm area. Table 2 summarizes the Sa and Sz values including an average value of the three measurements.

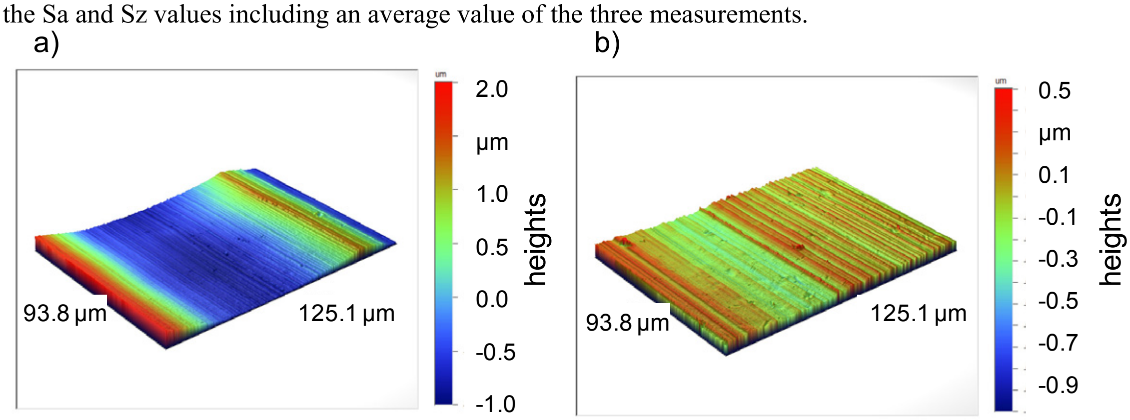

Fig. 4: (a) 3D-topography plot of the conventional insert; (b) 3D-topography of the wiper insert

Table 2: (3D-) Roughness values

Insert type	State of insert	Sa [nm]			Average [nm]	Sz [nm]			Average [nm]
Wiper	New	71	73	69	71	770	548	681	666
Wiper	Worn	96	94	91	94	766	776	770	771
Conventional	New	109	100	120	110	748	841	864	818
Conventional	Worn	112	110	127	116	1410	890	786	1029

When comparing these values to the values generated using the two dimensional Perthometer, there is a difference to be found. The roughness of the surface produced with a conventional insert does not decrease (but instead increases) with tool wear. This can be referred to the exclusion of the long waviness which varies between the different states of the tool wear.

Fig. 5a;b and Fig. 6a;b show the residual stress profiles induced in the workpiece using new and worn, wiper and conventional inserts. When analysing and comparing these plots, it becomes obvious, that the wiper insert induces higher compressive stresses than the conventional insert at all settings. Tool wear leads to a shift of compressive to tensile stresses.

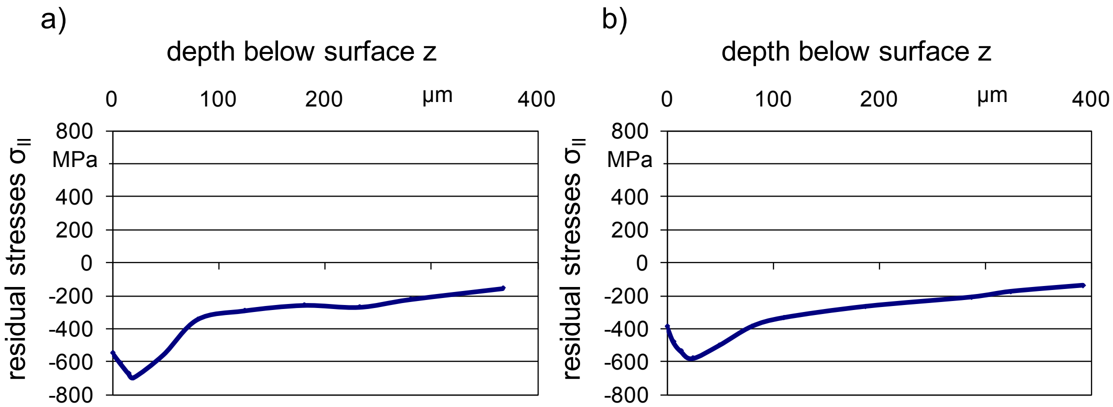

Fig. 5: Residual stress profiles induced by new (a) wiper insert; (b) conventional insert

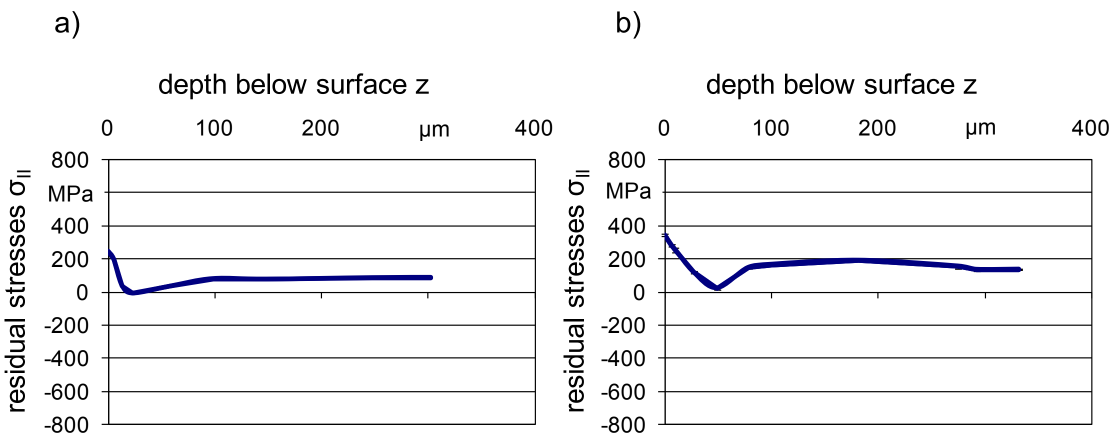

Fig. 6: Residual stress profiles induced by worn (a) wiper insert; (b) conventional insert

The subsurface of the workpieces is investigated using scanning electronic microscopy (SEM, not shown). It was found that the influence of the insert on the microstructure varies with the different tool geometries and tool wear (Note that white and dark layers are not found at any settings.) With increasing tool wear the microstructure is affected in greater depth and microstructural changes are more visible. The conventional insert mainly leads to flow lines in the material. These flow lines enlarge and grow into increasing depth (up to 4 µm) with increasing tool wear. When regarding the SEM pictures of the workpiece machined with a new and worn wiper insert, the flow lines are much less visible. Figures 7a and b show micrographs after machining with worn conventional and wiper insert respectively.

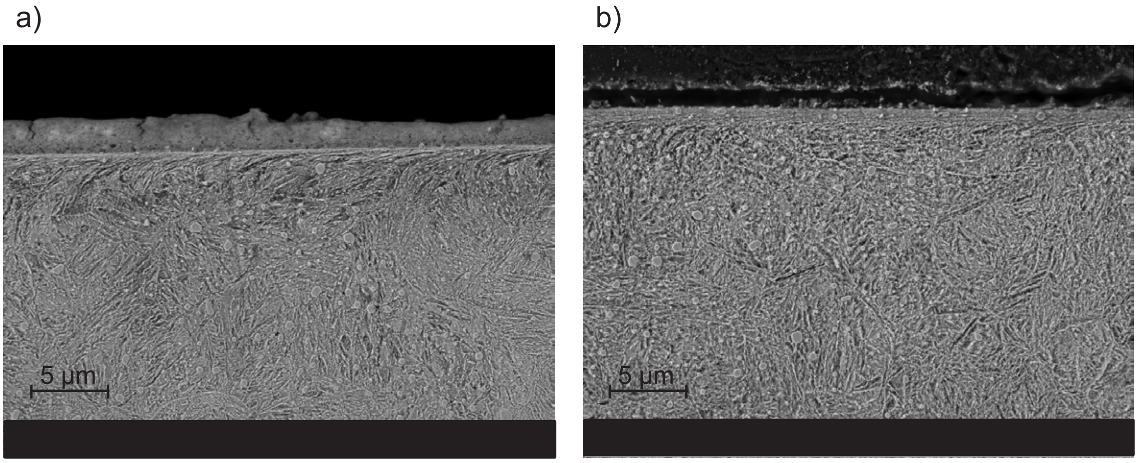

Fig. 7: Micrographs after machining with (a) conventional insert; (b) wiper insert

4. Discussion

To explain the decrease of surface roughness with increasing tool wear of the conventional insert, SEM pictures of the worn inserts are taken, (Fig. 8a;b). It can be seen, that the wear pattern differs. The depth of cut notch wear of the wiper insert is more sustained due to the large multi-radii. The depth of cut notch wear of the conventional insert is very smooth and can act as an unintentional multi-radius generated by the advancing wear.

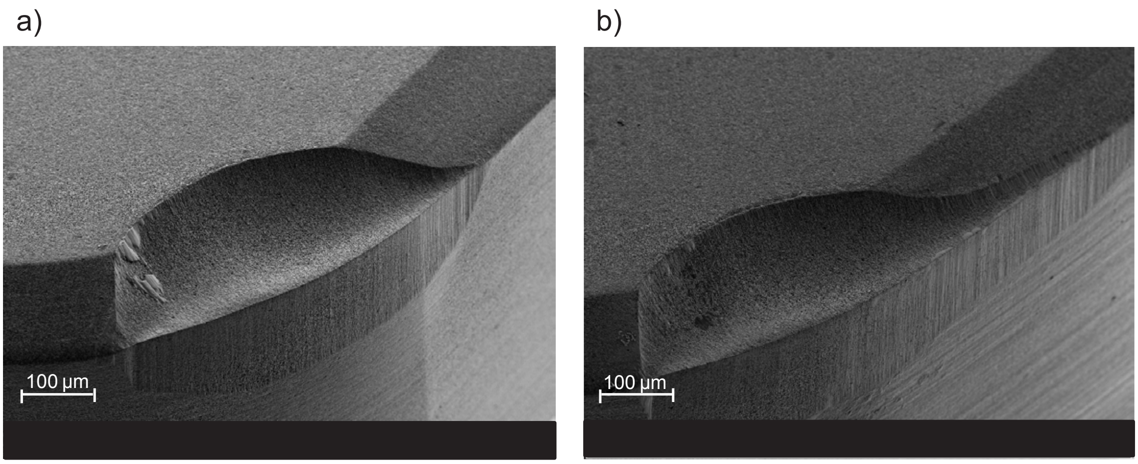

Fig. 8: (a) SEM picture of the worn conventional insert; (b) SEM picture of the worn wiper insert

The multi-radii of the wiper expand contact area of the tool and workpiece. The enlarged contact area increases the loads induced during the turning process. These effects can be the reason for the higher compressive residual stresses.

5. Conclusions

A model for surface roughness and force prediction was generated. The model makes further investigations easier by revealing that specific parameters, e. g. cutting speed, have no significant effects and can by that be excluded from further investigations. The insert type has an effect on surface roughness, forces and residual stress. For the chosen parameters, there are no FEM-based methods described in literature that are able to predict the residual stress profiles produced by applying wiper inserts in a quantitative way yet. However some first approaches in FEM-based methods including e.g. flow stress are presented by Klocke and Kratz [5]. Wiper inserts produce smoother surfaces within the range of the experiments conducted and are more stable when it comes to changes in feed and nose radius. While the surface roughness becomes greater when a worn wiper insert is used, a worn conventional insert produces superior roughness then a new conventional. The superior surface roughness achieved using a wiper insert comes along with cutting forces F_r and F_t being higher. By the wiper geometry the contact area of tool and workpiece is enlarged, thus inducing higher thermo mechanical loads (cutting forces and temperature). The higher loads lead to higher compressive residual stress. Summarizing it can be stated that using wiper inserts leads to superior surface integrity compared to conventional inserts. At the same time, higher productivity can be achieved.

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