ANALYSIS OF SURFACE INTEGRITY AFTER HARD TURNING WITH WIPER INSERTS

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This paper deals with analysis of surface integrity after hard turning with wiper insert. Surface integrity expressed in terms of surface roughness, microstructure and residual stress state is compared with conventional insert geometry. Structure and stress state after hard turning is also compared with the following super finished and ball burnished surfaces. The results show that wiper cutting insert enables obtaining surface of low surface roughness at high feeds as well as more favourable stress and structure state as opposed to those produced by conventional insert. Surfaces produced by wiper insert exhibit higher resistance against mechanical load as those induced by ball burnishing.

Keywords:
hard turning, wiper geometry, residual stress, structure, surface roughness

1. Introduction

It is well known that ground parts can sometimes suffer from over tempering induced by grinding cycle [Malkin 2007]. Therefore, premature failures of components in operation can occur due to early crack initiation. Being so, grinding cycles are nowadays replaced with hard turning in some cases. Compared to the grinding, hard turning is considered as a competitive operation in making a variety of components with the possible economy and other benefits. Hard turning operations are usually employed for machining of components of complicated geometry as well as when high removal rates are needed [Grzesik 2013, Tonshoff 2000]. The main advantage of grinding can be viewed in high speed in which surface is produced. Moreover, grinding is less sensitive to the cutting conditions (surface roughness depends on grinding wheel properties, mainly grain size) while feed takes major role in surface roughness of hard turned components. For this reason, specific wiper cutting insert geometry (see Fig. 1) was developed for turning operations. Such geometry makes longer contact area between cutting insert and workpiece.

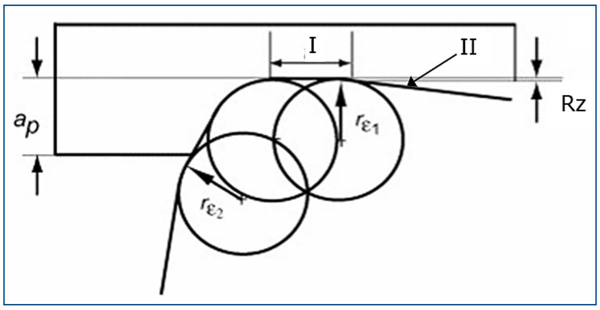


Figure 1. *Geometry of wiper insert, [Ozel 2007]*

Its influence on surface roughness was reported in many studies [Grzesik 2008] [Samardziova 2014] [Ozel 2007] [Elbah, 2013]. While conventional insert can keep surface roughness (expressed in Ra) below 2 µm at feed about 0,2 mm, wiper insert produces such surface roughness at much higher feed (beyond 0,5 mm). Effectiveness of wiper insert (from the point of surface roughness) is driven by ratio between feed and contact length of interface between cutting insert (minor cutting edge) and machined surface. This contact length is given mainly by the zone I (see Fig. 1) of zero tool minor cutting edge angle. Moreover the low tool minor cutting edge angle region also contributes to reduce irregularities on the produced surface (zone II in Fig. 1). Specific minor cutting edge geometry of wiper insert indicates that the produced surface undergoes the multiple contacts with the minor cutting edge to obtain quite smooth surface at high feeds while the repeated contacts are reduced when conventional geometry is employed. However, such surfaces (produce by conventional and wiper geometry) would differ not only from the point of view of surface roughness. It should be also claimed that except surface roughness surface integrity can be expressed in such terms as residual stress state, microstructure, microhardness, ect. It is well known that surface integrity should be investigated in complexity of parameters since they affect functionality of components in operation. Application of wiper inserts in hard turning cycles is mostly reported from the point of view of surface roughness but stresses state and microstructure structure would also differ. For this reason, this paper deals with more complex investigation of surface integrity of components produced by hard turning (of conventional and wiper geometry) as well as combination of hard turning and the following superfinishing or ball burnishing. Superfinishing is routinely employed in the bearing industry after grinding or hard turning to achieve smooth surface while ball burnishing would induce surface hardening.

2. Experiments

Experiments were carried out on bearing steel 100Cr6 of hardness 61 HRC. The samples of external diameter 55 mm and width 30 mm were machined in 3 series as follows:

- hard turned by conventional and wiper insert at variable feeds,
- hard turned at feed 0,225 mm and superfinished afterwards,
- hard turned at feed 0,225 mm and ball burnished afterwards.

Cutting and other conditions are listed in Table 1.

	Tool	Cutting conditions
Hard turning Conventional geometry	cutting insert SNGN 120408 T01020, Mixed ceramics containing 71% of Al_2O_3 and 29% TiC $r_\varepsilon = 0{,}8$ mm, $b_\gamma = 0{,}1$ mm, $\gamma_n' = -20°$	$v_c = 150$ m.min^{-1}, $f = 0{,}09 \div 0{,}65$ mm, $a_p = 0{,}15$ mm
Hard turning Wiper geometry	Cutting insert SNGN 120408 T01020, T01020 WG, $r_\varepsilon =$ wiper, $b_\gamma = 0{,}1$ mm, $\gamma_n' = -20°$	
Superfinishing	A99A320N10 V	$v_c = 150$ m.min^{-1}, $f = 0{,}09 \div 0{,}65$ mm, $a_p = 0{,}15$ mm, $F = 40$ N, $A = 3{,}5$ mm, grain size 29 µm, coolant: 85% petroleum and 15% oil
Ball burnishing	3 passes of ball of diameter 12 mm	$F = 40$ N, coolant: 85% petroleum and 15% oil

Table 1. *Cutting conditions*

Machined surface were analysed from the following points of view:

- surface roughness (*Ra, Rsk, Rku, Rmr(20)* parameters and Abbot curve),
- residual stresses,
- microstructure.

Surface roughness for each sample was measured by Hommel Tester T 2000. *Ra, Rsk, Rku and Rmr(20)* values were determined by averaging of 3 measurements (analysed length 4 mm). Samples for metallographic observation were routinely prepared by cold sectioning, hot moulding, grinding, polishing and etching (5% Nital etch for 10 seconds). Microstructure was observed in the direction of cutting speed. Residual stresses were measured by mechanical method [Neckar 1985] based on eletrolythical etching (2 hours, 20 %

concentration of H_2SO_4 – electrolyte, 5V and 6A) machined surface and simultaneous measurement of a ring deformation. The details about principle, mathematic apparatus and measuring unit can be found in [Neckar 1985].

3 Results of experiments

3.1 Surface roughness

Fig. 2 illustrates the typical profiles of surface roughness for conventional and wiper inserts. Amplitude of peaks in the surface roughness profile is strongly reduced when the surface is produced by wiper insert. Contact land of zero tool minor cutting edge angle smoothes the produced surface within investigated feeds as Fig. 3 illustrates. Surface roughness produced by wiper insert is kept low and remarkable increase of *Ra* can be found for surface produced by conventional insert geometry. *Ra* values are approximately 4 times higher for conventional geometry compared to the wiper ones at higher feeds. Fig. 3 also demonstrates lower sensitivity (when wiper geometry is employed) to variable feed rates. It should be also noticed that such parameters as *Rq, R*Δ*q* or *Rz* exhibit nearly the same differences within the analyzed feed.

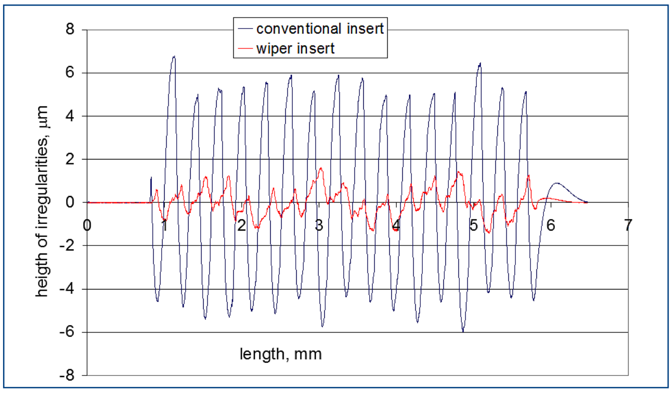


Figure 2. *Surface roughness profiles, f = 0,3 mm*

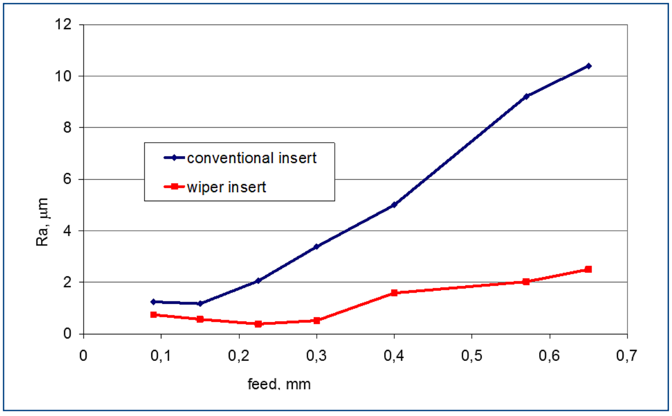


Figure 3. *Surface roughness Ra versus feed*

Hard turning is usually followed by superfinishing process to smooth the surface and enlarge the real contact area of bearing elements in operation. Surface roughness expressed in Ra parameter is reduced and attains 0,058 µm for both surfaces prepared either conventional or wiper inserts. Superfinishing completely removes profile peaks produced by previous operation. Profile after superfinishing consists of very fine furrows, small reminders of the valleys produced by hard turning. These furrows serve as micro reservoirs of oil enhancing the lubrication of bearing contact surfaces in operation. Furthermore, negative skew of the surface profile (expressed in its *Rsk*, coefficient of asymmetry) is preferred for bearings or other components exposed to cyclic contact load. Surface of negative skew contains mainly valleys while peaks are reduced. Fig. 4 shows that wiper insert mostly produces profile of negative *Rsk* since its tool minor cutting edge angle strongly reduce profile peaks as opposed to conventional insert. Positive *Rsk* values are produced by wiper insert at quite large feed 0,65 mm when tool minor cutting edge is deflected far away from the produced surface and smoothing effect becomes ineffective. Fig. 4 also shows that profile curtosis, expressed in *Rku* parameter (based on density of surface irregularities distribution) for surfaces produced by wiper insert are closer to the standard value 3 than those produced by conventional insert. Expressed in other words, conventional insert produces the surface in which high peaks dominate, thus *Rku* of such surface falls far away below 3 than the profiles produced by wiper insert. Only the low feed (0,09 mm) producing low *Ra* allows getting the surface of higher *Rku*.

Compared to hard turning, superfinishing produces the surface of *Rsk* = - 0,94 and *Rku* = 4.49. Compared to the surface produced by conventional insert, superfinishing process enhances the surface roughness more remarkable than hard turning performed by wiper insert. On the other hand, ball burnishing does not allow getting the acceptable surface roughness. Ball burnishing produces the wavy profile of *Ra* = 0,59 µm, *Rsk* = 0,016 and *Rku* = 2,1 as the surface comparable with the surfaces produced by conventional insert.

Significant distinctions in surface roughness character can be also demonstrated by the use of Abbot curve, see Fig. 5. It is well known that wear rate of the surface exposed to the cyclic load depends on contact area between the surface and its distribution in the near surface region. Low contact area increases local stresses within the entire contact, thus accelerates the wear rate which in turn decrease dynamic stability of a bearing, escalates its vibrations and noisiness. Being so, Abbot curve and the corresponding contact area favour superfinished surfaces giving *Rmr(20)* = 96 % while hard turned surface (produced by conventional insert) only 75%. However, wiper geometry produces the surface of *Rmr(20)* = 91% due to reduced peak heights; ball burnishing gives *Rmr(20)* = 88%.

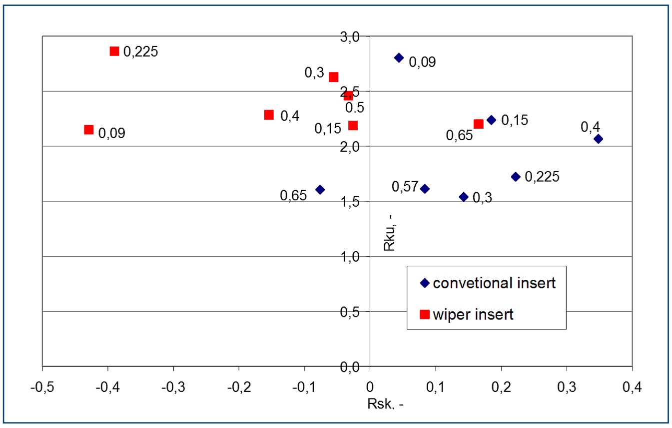


Figure 4. *Rsk versus Rku*

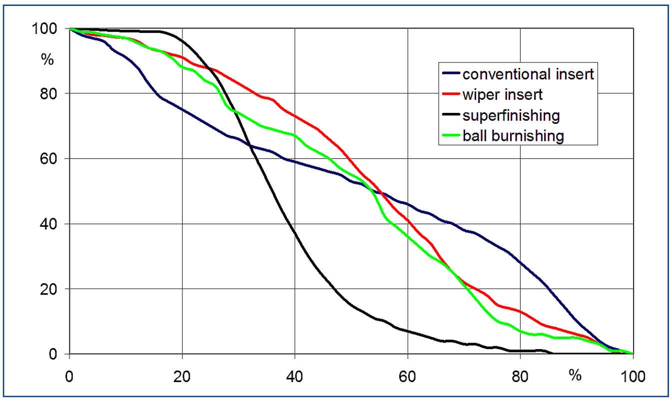


Figure 5. *Abbot curves for different surfaces*

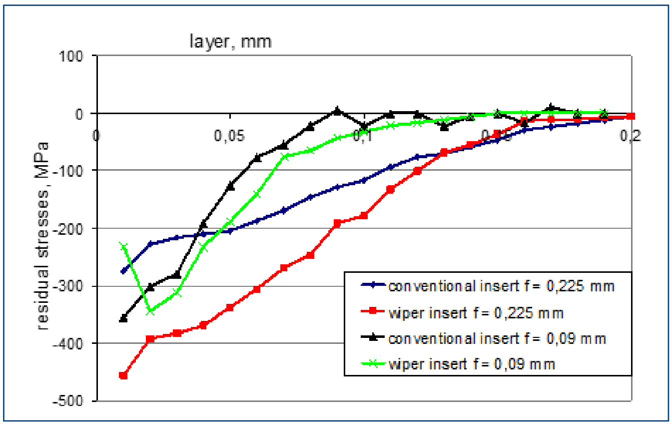


Figure 6. *Residual stress profile after hard turning*

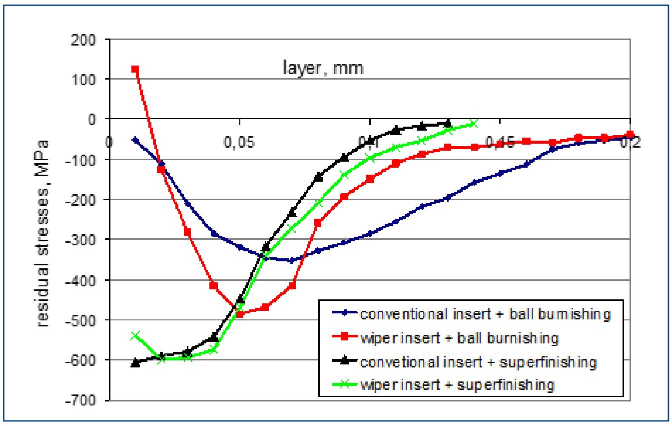


Figure 7. *Residual stress profile after hard turning (f = 0,225 mm) followed by superfinishing or ball burnishing*

3.2 Residual stresses

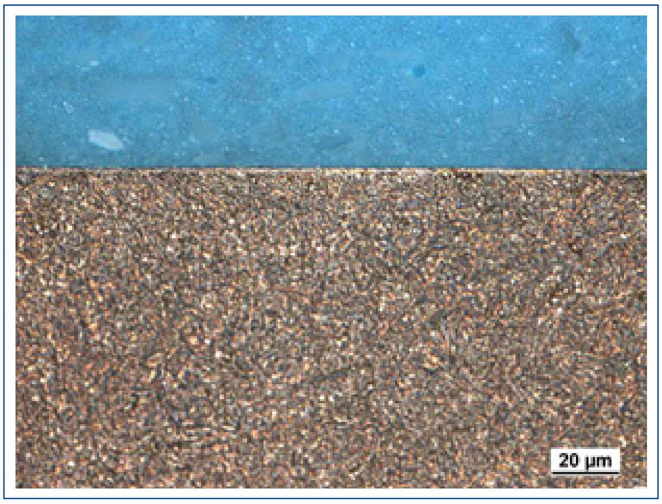
I - type residual stresses in machined surface are due to unbalanced plastic deformation and/or thermal expansion between the near surface region and the core. Moreover, structure transformation can also take significant role especially in hard turning operations. Compressive stresses produced by hard turning, shown in Fig. 6, indicate that thermal effect (producing mainly tensile stresses) is minor and high contact pressure in the tool – workpiece dominates. The significant aspect of the stress state after hard turning is associated with multiple contacts between produced surface and tool with regard tool geometry, mainly tool minor cutting edge angle and flank wear VB. Keeping nearly constant VB the main reason for different residual stress profile at higher feed can be linked with cooling rate of the surface. Near surface region of machined surface undergoes the fast heating followed by rapid cooling. However, wiper zero tool minor cutting edge angle slows down cooling rate since the produced surface undergoes the multiple contacts with minor cutting edge. Therefore rapid cooling is interrupted during the next workpiece revolution.

Higher compressive stresses produced by wiper insert at higher feed 0,225 mm is due to slowed cooling rate as well as repeated process of plastic deformation of the near surface region with regard of large elastic deformations of hard structure [Micietova 2014]. Fig. 6 also shows nearly the same stress profiles for conventional as well as wiper geometry at low feed 0,09 mm when the effect of multiple tool – workpiece contacts takes place and surface roughness is kept low for both inserts. As soon as the surface roughness considerably increases, the different mechanism in which the machined surface is produced result in remarkable distinctions in residual stress profile. Slowed cooling rate can be also evidenced by micrographs of machined surface. Surface produced by conventional insert contains thin white layer (WL) of variable thickness whereas wiper geometry produce WL free surface, see Fig. 8a, b.

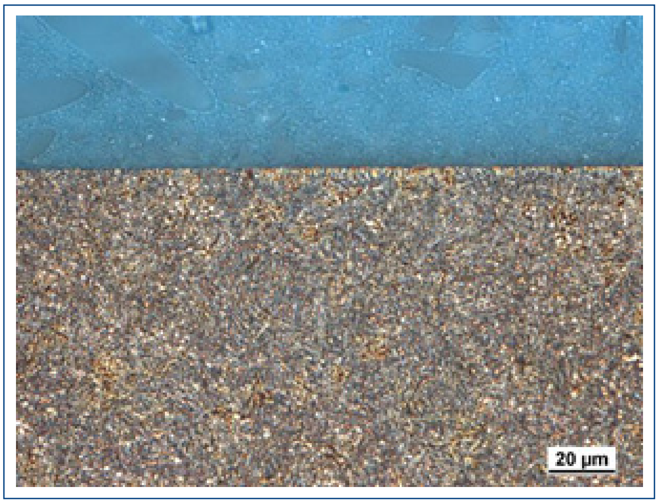
On the other hand, superfinishing process eliminates distinctions produced by previous operation. Fig. 7 illustrates that combination of the different insert geometry and the following superfinishing allows getting nearly the same stress state. Compared to the hard turning, magnitude of compressive stresses increase and thickness of the stress affected layer decreases.

3.3 Microstructure

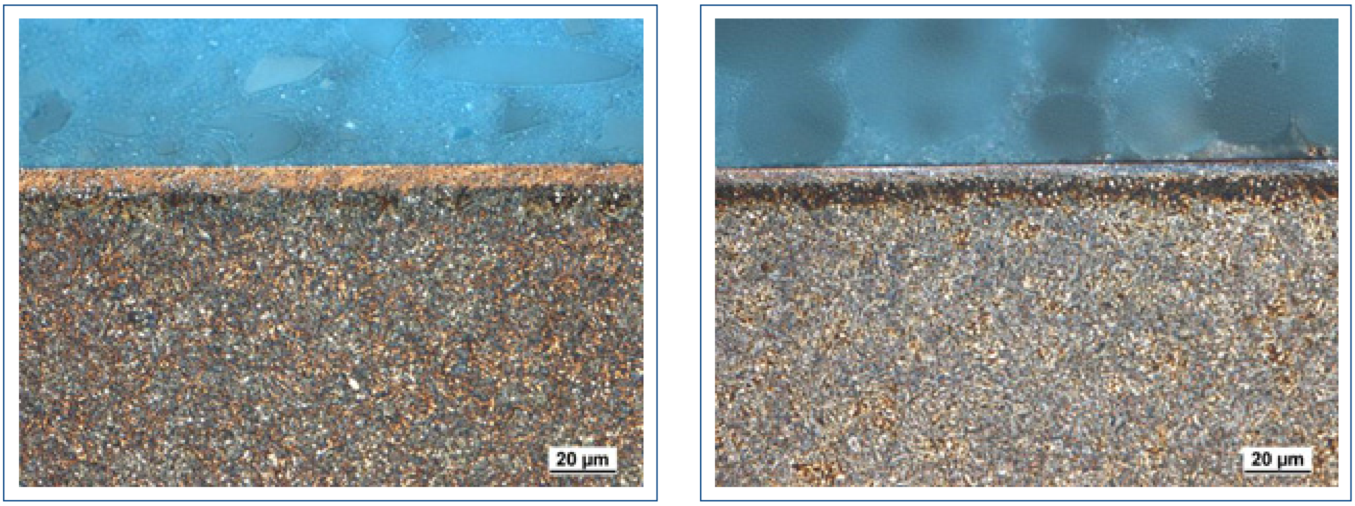
Ball burnishing dramatically alters stress profile as Fig. 7 illustrates. Micrographs of ball burnished surface (see Fig. 8c, d) indicates that dynamic recovery takes place. Near surface region structure (which appears white in the optical image) is refined as a result of structure transformation. WL is followed by the heat affected zone (HAZ) appearing dark in deeper regions. Fig. 8c shows that thickness of WL produced by conventional insert + ball burnishing is about 8 μm. HAZ is less visible, discontinuous of variable thickness. On the other hand, wiper insert + ball burnishing produces WL of thickness 6 μm and dark continuous HAZ of nearly the same thickness, see Fig. 8d. Dynamic recovery in the near surface region remarkably alters stress distribution as Fig. 7 illustrates. Either magnitude of compressive stresses is reduced or low tensile stresses are achieved.



8a) after hard turning, conventional insert, f = 0,225 mm



8b) after hard turning, wiper insert, f = 0,225 mm



8c) after hard turning (conventional insert, f = 0,225 mm) and ball burnishing

8d) after hard turning (wiper insert, f = 0,225 mm) and ball burnishing

Figure 8. *Microstructures of machined surface*

Ball burnishing is usually performed on plastic metals to induce mechanical strengthening of the surface with regard its resistance against cyclic contact load, corrosion resistance, etc. This operation is usually not recommended for steels of strength above 1400 MPa [Gasparek 1979]. Steels of hardness 61 HRC (exceeding this critical value) behave in a brittle manner at ambient temperature. Limited (or nearly no) plasticity of such structure can cause surface cracking after ball burnishing as Fig. 9 illustrates.

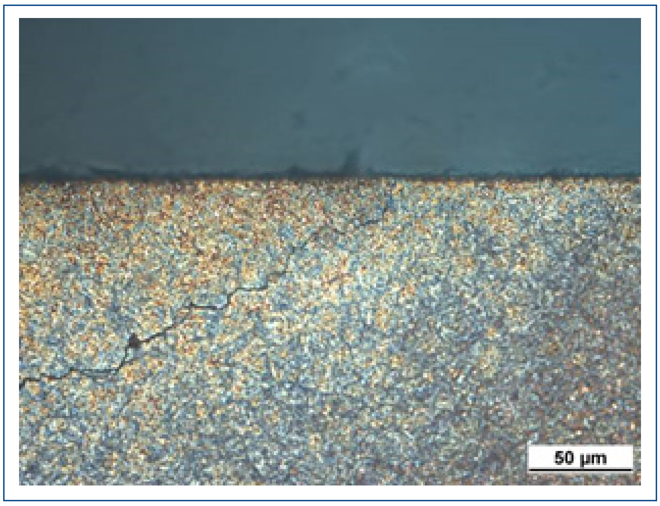


Figure 9. *Crack initiation after ball burnishing*

4. Conclusions

Quality of bearings is crucial for functionality of machines in operations. Superfinishing is still preferred from the various point of view such as surface roughness, stress state or structure. On the other hand, this study indicates that ball burnishing modifies the machined surface in the improper manner due to thick WL, unfavourable stress state and micro cracks initiation. Compared to the conventional insert geometry, wiper geometry improves surface roughness expressed in many parameters, magnitude of compressive stresses at higher feeds as well as eliminates formation of unfavourable WL in the near surface regions. Nowadays, grinding cycles are very often replaced by hard turning. Combination of roughing cycles (performed by wiper inserts) followed by grinding or superfinishing can increase productivity in bearing industry without any unfavourable impact on surface integrity together with comparable purchased cost and tool life (compared to the conventional insert geometry).

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