Technical Paper

Influence of cutting edge geometry on tool wear performance in interrupted hard turning

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1. Introduction

Some of the advantages of using turning instead of grinding for the finish machining of hardened steel surfaces are: high flexibility, the ability to cut complex surfaces with a single machine setup, cost of the process and the possibility of machining without cutting fluid [1]. Otherwise, turning of hardened steels with interrupted surfaces presents some restrictions, due to the fact that the tools usually used for this purpose are brittle, and therefore, have only little resistance against the typical shocks of interrupted cutting. However, a very large number of industrial parts present some kind of interruption on their surfaces, which made the study of turning of interrupted surfaces of hardened steels very important [2].

One difference between continuous and interrupted cutting is that the latter, during engagement, does not have the thermal softening effect from the shear zone. This results in higher initial cutting forces. The mechanical impact due to such a rather sudden rise of the cutting forces induces transient vibration [3].

The interrupted cutting process has three characteristic features: tool entry into the workpiece, tool exit and cyclic loading and unloading accompanied by cyclic heating and cooling. The relative importance of these depends on the dimensions of the cut, the cutting speed, the heating time/cooling time, the workpiece and tool materials, the shape of the tool and the geometry of the entry and exit [4]. According to Pekelharing [4], tool entry, formerly considered to be the major danger point, is only a jump in the cutting force from zero to its normal value. This could be dangerous at the beginning of the cut, since the main cutting force is supported by only a narrow strip of the rake face. The same author affirms that the tool exit can be even more important regarding tool life due to a “negative shear zone” formed at the exit of the workpiece. He explains that the usual shear zone with a positive shear angle stops functioning when a negative shear zone occurs. The positive shear zone exists with a positive normal pressure, i.e. with compressive stress normal to the shear movement. The negative shear zone lacks this pressure or has to work under tensile stress and fails to maintain continuity. Before the pressure between the rake face and the chip fails to zero the total pressure is concentrated near the edge on a narrow strip with a width of about one-third of the thickness of the cut. This stress reversal can lead to tool failure. In their investigations Ghani et al. [5] verified that the stress reversal is stimulated by higher cutting velocities.

Alternating heating and cooling cycles, which cause high temperature gradients, also have to be considered in interrupted cutting. It has been known that thermal stresses due to cyclic temperature gradients, called “thermal shock”, are the main mechanism of thermal cracking, a detrimental phenomenon to tool life. However, in interrupted cutting, cutting temperature variations also depend on cut and non-cut durations. Thus, it is possible that cutting tools may not reach saturated temperatures, as in continuous cutting, for a shorter cut period, and similarly, may relax to
lower temperatures for a longer non-cut period, and therefore, restore hardness and other properties [3].

In order to reduce the influence of such wear causes and increase tool life, CBN has been widely used in interrupted cutting of hardened steels, because of its high hardness, high thermal conductivity and low thermal expansion coefficient. Tools with high CBN content are usually recommended for turning of hardened steels with interrupted surfaces due to their higher hardness and toughness in comparison to low CBN content tools [1].

Chou and Evans [3] suggest that greater hardness and fracture toughness of high CBN content tools result in better wear resistance to mechanical impact. However, the metallic binder (cobalt or aluminum) in such tools accelerates tool wear at high cutting speeds due to its affinity with workpiece materials. Godoy and Diniz [6] analyzed the wear mechanisms of high content CBN tools in interrupted cutting and observed that attrition with pulled out particles was the main wear mechanism. They suggest that, when removed from the tool, these particles probably cause abrasion mainly when chip thickness is small and cutting pressure is high. Moreover, they affirm that attrition may have been favored by the presumably low cohesion between CBN and the binder material. Differently, the application of low CBN content inserts in interrupted hard turning by Pavel et al. [7] led to notch wear and small chipping of the cutting edge. The authors attributed the wear pattern to the thermal and mechanical shocks produced by the interruptions.

A reduction of tool wear in interrupted hard turning can also be reached by a suitable preparation of the cutting edge. According to Pekelharing [4], a chamfered or rounded edge can postpone or eliminate tool failure, but the feed force of a well-chamfered cutting tool may be two or three times higher than that of an otherwise identical sharp tool and correspondingly the rate of flank wear may also be much higher. This means that the chamfer must be optimized so that just enough protection is obtained. Results from Dokainish et al. [8] indicate that for the cases in which the thickness of the cut is small compared to the chamfer width, the magnitude of the shear stresses near the cutting edge increases significantly when the chamfer angle is increased from 5° to 20°.

Diniz and Oliveira [1] demonstrated that the interaction between cutting edge geometry and tool material has a significant influence on the tool life. They observed that tools with edge rounding exhibited longer lives when a high CBN content tool was used, and chamfered tools had longer lives when a low CBN content tool was used. Edge rounding makes the edge more rigid and resistant to chipping and breakage. On the other hand, it causes a greater chip deformation due to the lower rake angle, especially when a small chip thickness is used.

Considering that an appropriate combination of tool material and cutting edge preparation can decrease tool wear, this paper proposes investigating the tool wear performance of customized cutting edge geometries, prepared in CBN inserts by grinding, in interrupted hard turning. The investigation of the use of such micro geometries in this process is motivated by the improvement of tool life obtained by these edge geometries in continuous hard turning in comparison to inserts prepared with single chamfers [9].

2. Material and methods

The applied inserts have the specification SNMA120408 and eight CBN corners brazed on a cemented carbide substrate of grade K10-20. The CBN part is composed of 90% CBN, and TiCN and Co as bond materials. CBN grain size is approximately 4 μm and its Vickers hardness is 36.4 ± 0.48 GPa. The inserts are ground (grinding of flank faces and edge preparation) in a five-axis grinding machine type Wendt WAC 715 Centro with a maximum rotation of the grinding wheel of 1625 rpm and a maximum spindle power of 3 kW. A diamond grinding wheel with grain size D15, concentration C120 and vitrified bonding is used with the following parameters: axial feed rate \( v_{fA} = 4 \text{ mm/min} \), rotational speed of the insert to grind corner radius \( n = 2778/ \text{min} \), and cutting speed \( v_c = 20 \text{ m/s} \). In order to avoid wheel clogging and profile wear, the grinding wheel is continuously dressed with a dressing roll \( \text{Al}_2\text{O}_3 \) 220 mesh and an axial dressing feed rate \( v_{fa} = 1 \text{ μm/s} \).

Cutting edges of CBN inserts are prepared with the method developed in Denkena et al. [10]. Here, the general edge roundings are discretized by several chamfers. Chamfers are characterized by chamfer width and angle, while edge roundings are characterized by the cutting edge section at the rake face \( S_r \) and the cutting edge flank at the flank face \( S_f \). The form factor \( K = S_r/S_f \) defines the tendency of the cutting edge to the rake (\( K > 1 \)) or to the flank face (\( K < 1 \)). In case of a symmetric rounding (\( K = 1 \)), the edge radius \( r_β \) will be used instead of \( S_r \) and \( S_f \). Five sorts of micro geometry are tested in interrupted hard turning (Fig. 1): sharp edge, single chamfer (chamfer width \( b = 100 \) μm and chamfer angle \( γ = 26° \)), asymmetric rounding \( (K = 2.0) \) \( (S_r = 100 \) μm, \( S_f = 50 \) μm), symmetric rounding \( (K = 1.0) \) \( (r_β = 50 \) μm) and asymmetric rounding \( K = 0.5 \) \( (S_r = 50 \) μm, \( S_f = 100 \) μm). All edge roundings are discretized by three chamfers, which are shown in Fig. 1. A Mahr Perthometer is used for obtaining the profile of the ground micro geometries. The characteristic geometric values have been determined by the profile plots and the standard deviations are under 10%.

Turning tests are conducted in a Gildemeister CNC lathe type MD105, which has a maximum rotational speed of 10,000 rpm and maximum power of 50 kW. Cutting speed \( v_c = 200 \text{ m/min} \), feed rate \( f = 0.05 \text{ mm/rev} \) and depth of cut \( a_p = 0.05 \text{ mm} \) are kept constant. Cylinders of 16MnCr5 steel with hardness 60 ± 2 HRC and length 200 mm are turned without cutting fluid. The interruptions consist of two longitudinal rectangular channels (depth = 1 mm (for maximum diameter), width = 8 mm) with an offset of 180° in tangential direction (Fig. 2). During the tests, the diameter of the cylinders is allowed to vary from 65 mm to 62 mm, so that the variation of the impact frequency due to the interruptions is lower than 5% and does not affect the results.

Maximum tool flank wear is controlled through a digital microscope Keyence VHX-600 and pictures of the tool wear are recorded through a scanning electron microscope Zeiss EVO 60 at the end of the tests. The tool life tests are carried out up to a length of 800 mm (approximately 16 min). Aiming to investigate the influence of micro geometry on the process forces without considering tool wear, these are measured in a cutting time of 2 min. Cutting feed and passive forces are acquired by a Kistler three-component-dynamometer type 9129A Al linked to a Kistler charge amplifier type 5015. An acquisition rate of 2500 Hz and a low pass filter with cutting frequency of 1000 Hz are applied. For calculating average force values, only workpiece full parts are considered, while interrupted parts are neglected.

Turning tests were repeated in order to ensure the reliability of the obtained results.

3. Results and discussion

Since the effect of different edge geometries on tool performance is addressed in this paper, it is appropriate to define the edge sharpness. According to Stepien [11], the edge sharpness strongly depends on the geometrical characteristics of the edge, as well as the tool and work materials and the kinematics of the process. In accordance with Outeiro and Astakhov [12], considering the characteristics of machining processes, sharpness is a relative parameter, which depends on the ratio of the uncut chip thickness and the tool cutting edge radius (relative tool sharpness). Even if the tool cutting edge radius is small, it may have a significant
influence on the cutting process if the uncut chip thickness is of the same order or even smaller than the cutting tool edge radius. However, this ratio does not consider the effects of chamfers and asymmetric roundings, as described in Denkena et al. [10], on the chip deformation, stagnation zone and ploughing effect. Regarding this matter, in this work a cutting edge will be considered sharp when the contact length between cutting edge and workpiece/chip is at a minimum. Thus, the bluntness increases with the increase of the contact length.

Bearing this in mind, the process forces for the different micro geometries can be analyzed. An increase of the forces with the bluntness of the edge geometry can be observed in Fig. 3. Though a lower increase is noted for the first three geometries (sharp, chamfer and \( K = 2.0 \)), higher values can be seen for the last two (\( K = 1.0 \) and \( K = 0.5 \)). The noticeable high deviations observed for the micro geometry \( K = 0.5 \) are due to the vibrations related to the higher force components.

Higher force values can be related to the increase of chip deformation and stagnation zone in front of the tool, due to the larger bluntness of the edge and higher negative rake angle, since the chip is formed at the edge region. Moreover, as it can be seen in Fig. 4, under consideration of a constant average chip thickness \( (h_m = 8 \mu m) \), taking into account the effects of edge geometry and corner radius [13]), the contact length between edge geometry and workpiece is increased with the decrease of the form factor. Thereby, an increase of the friction can also be considered a factor for the increase of the process forces.
High process forces demand high power to perform the operation. This power is mainly transformed into heat in the three shear zones. Most of the heat from the primary and secondary shear zones is dissipated into the chip, some heat (mainly from the tertiary shear zone) increases the workpiece temperature and some heat (mainly from the secondary and tertiary shear zones) is conducted into the tool edge. Therefore, high forces contribute to high cutting temperature [14]. Since tool wear in interrupted cutting is mainly caused by mechanical and thermal loads, higher flank wear values are expected for micro geometries with reduced form factors. Accordingly, an increase of the flank wear width from the chamfered edge to the edge rounding with K = 0.5 for a fixed cutting time can be observed in Fig. 5. Larger contact lengths toward the flank face (larger values of $S_n$) also contribute to this increase of flank wear (Fig. 4).

The sharp edge showed, however, a worse result when compared with the chamfered tool, though the load on the edge is the lowest in comparison to the other micro geometries. In this case, the sharp edge could not withstand the mechanical load generated during the process. Moreover, Fig. 4 shows that the forces acting on the sharp edge are parallel to the flank face, leading to a small supporting effect. Therefore, a compromise between reinforcement of the cutting edge and increase of mechanical and thermal loads can be achieved by a chamfered tool in the case of interrupted cutting.

Fig. 6 demonstrates the tool wear of different edge geometries after a cutting time of 16 min. In all situations a gradual flank wear is observed. Explained by the uneven worn surfaces and adhered material on flank faces, the main wear mechanism for all micro geometries corresponds to attrition, defined by the rupture of microscopic fragments of the tool after a strong adhesion of workpiece material. According to Trent and Wright [15], a rapid destruction of tool edge occurs mainly in operations involving interruptions of cut, or where vibration is severe. Small uncut durations did not encourage the formation of thermal cracks, but have led to an increase of the temperature, which can have contributed to the adhesion of workpiece material on tool wedge.

Due to the low contact length between edge and workpiece (Fig. 4) toward the rake face (defined by the edge geometry,
undeformed chip thickness and tool positioning in relation to the workpiece) as well as discontinuous chips because of the interruptions, poorly developed crater wear is noted in all CBN inserts.

In comparison to sharp and chamfered edges, deeper grooves are noted in micro geometries with form factors $K = 2.0, 1.0$ and 0.5 due to the higher temperatures involved. A large expansion of the tool surface (tool–chip interface) is caused by elevated temperatures during cutting. At the same time, tool sub-surface is submitted to a smaller expansion, due to the lower temperatures. As a consequence, the sub-surface will hinder a larger expansion of tool surface, causing compressive stresses. With the reduction of temperature (during workpiece interruption) tool surface is submitted to tensile stresses, while tool sub-surface undergoes compressive stresses. This stress variation is repeated with the temperature fluctuation. After a certain time, surface cracks occur. These cracks originate small grooves, which increase with time [16].

The breakage of the rake face of the tool with form factor $K = 0.5$ at the end of the test (cutting time = 16 min) can have occurred as a result of the higher forces and deeper grooves formed at the flank face, which reduced the supporting effect. The damage happened where the undeformed chip thickness has its maximum value because in this location the tool cutting edge undergoes the highest stress and temperature compared with other locations [17].

In any case, explicit edge chipping is not observed, which leads to the conclusion that under the considered cutting conditions the toughness of the cutting tool material (high CBN content) was enough to prevent failures of the tool during its entry (impact) or exit (formation of negative shear zone).

4. Conclusions

The influence of the cutting edge geometry on the performance of high content CBN inserts applied in interrupted hard turning was investigated. Not only the best edge geometry for the described task was found, but main wear causes and mechanisms were analyzed.

Regarding the reduction of tool wear in interrupted cutting and considering the tested micro geometries, a compromise between reinforcement of the tool edge and increase of mechanical and thermal loads can be achieved by a single chamfered tool. The decrease of the form factor of discretized cutting edge roundings leads to the increase of contact length between cutting edge and workpiece, which increases the load acting on the tool as well as tool wear. Otherwise, a cutting edge without a targeted preparation also leads to increased tool wear.

Main wear mechanism observed in all situations corresponds to attrition and because of the small uncut durations, no thermal
cracks are observed. Due to the positioning of the cutting edge in relation to the workpiece, the edge geometry, the dimension of the undeformed chip thickness and the discontinuous chips generated, crater wear is mainly limited to the edge region. Finally, taking into account the applied cutting parameters, the toughness of the high CBN content tool was enough to avoid tool failure at its exit or exit.

Further research activities will consider the use of finite element method in order to investigate thermo-mechanical loads on different edge geometries. Thereby, a quantitative analysis of the effect of edge geometry on tool wear can be given.

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References


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