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Influence of tool wear on surface roughness in hard turning using differently shaped ceramic tools

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Abstract

Hard turning has been applied in many cases in producing bearings, gears, cams, shafts, axels, and other mechanical components since the early 1980s. Mixed ceramics (aluminum oxide plus TiC or TiCN) is one of the two cutting tool materials (apart from PCBN) widely used for finish machining of hardened steel (HRC 50–65) parts, especially under dry machining conditions and moderate cutting speed ranging from 90 to 120 m/min. This paper reports an extensive characterization of the surface roughness generated during hard turning (HT) operations performed with conventional and wiper ceramic tools at variable feed rate and its changes originated from tool wear. Moreover, it compares some predominant tool wear patterns produced on the two types of ceramic inserts and their influence on the alteration of surface profiles. After the hard turning tests, the relevant changes of surface profiles and surface roughness parameters were successively registered and measured by a stylus profilometer. In this investigation, a set of 2D surface roughness parameters, as well as profile and surface characteristics, such as the amplitude distribution functions, bearing area curves and symmetrical curves of geometrical contact obtained for the machined surface, were determined and analyzed. A novel aspect of this research is that the notch wear progress at the secondary cutting (trailing) edges was found to produce the substantial modifications of the individual irregularities, and constitute the altered surface profiles. Moreover, this research contributes to practical aspects of HT technology due to exploring the relations between the tool state at different times within the tool life and the relevant surface roughness characterization.

Keywords: Hard machining; Mixed ceramic tools; Cutting tool geometry; Tool wear; Surface roughness

1. Introduction

It is obviously, known that machining of hardened steels belongs to the leading manufacturing technologies revolutionizing many branches of industry, especially bearing, automotive and die and mold sectors. The reason for such extensive applications is that hard machining (HM) of steel workpieces harder than 60 HRC with PCBN and mixed ceramic cutting tools can be essentially performed as rough, precision, and high precision operation when the R_z parameter is less than 1 μm [1,2]. In particular, precision finishing of hardened steel components using superhard cutting tools offers manufacturers an attractive alternative to traditional grinding. In particular, it can often cut manufacturing costs, decrease production time, improve overall product quality and eliminate environmentally harmful cooling media [1,3,4]. According to many industry reports, hard machining covers turning, milling and broaching, generally semi-finishing and finishing, operations. Gears and axles, and bearing components are typically turned parts, while milling is preferable in the die and mould industry [1,4,5]. It is obviously known that hard machining requires a negative rake angle along with the cutting edge reinforcement by a chamfer, and machine tools with very high stiffness and able to compensate thermal distortions of parts. Recently, multi-radii tool nose shaping, known as Wiper geometry [5] shown in Fig. 1b, and inserts with variable chamfer angle and width [6] are successfully employed. The first one results in a substantial improvement of the surface finish for

Abbreviations: a_p, depth of cut; f, feed rate; r_ε, radius of the tool corner; $r_{\varepsilon 1}$ and $r_{\varepsilon 2}$, radii of wiper curvature; r_{bo}, radius of smoothing part of wiper insert; v_c, cutting speed; R_a, the centre line average; R_{ku}, kurtosis; R_{max}, maximum roughness height; $R_{mr}(c)$, material ratio at depth c; R_{pk}, the reduced peak height; R_{Sm}, the average peak spacing; R_{sk}, skew; R_z, the valley-to-peak height; $R_{\Delta q}$, the RMS (root mean square) average slope; VB_C, corner wear indicator; VB_{max}, the maximum wear-land width in the B zone (see Fig. 1); ADF, the amplitude density function; CT, conventional tool; HT, hard turning; HPT, hard part turning; MC-HT, hard turning using mixed ceramic tools; WT, wiper tool.

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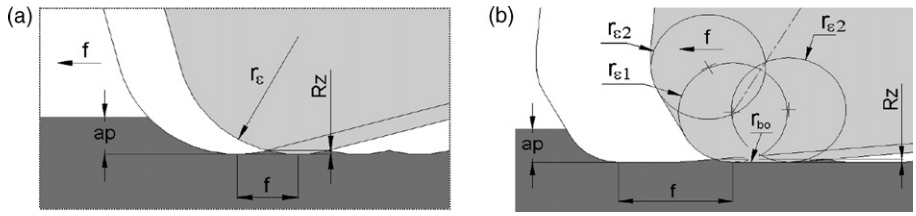

Fig. 1. Comparison of inserts with conventional geometry: (a) and wiper shape; (b) symbols: f feed; a_p depth of cut; r_ε radius of the tool corner; $r_{\varepsilon 1}$ and $r_{\varepsilon 2}$ radii of wiper curvature; r_{bo} radius of smoothing part; R_z valley-to-peak height.

turned parts, even for higher feed rates, and ensures distinctly higher productivity when using both ceramic and CBN inserts [5,7].

Many previous investigations of surface finish in hard turning (HT) operations with mixed ceramic and low content CBN (CBN–L) tools, as for example [1,8–10], documented only achievable values of the R_a parameter about 0.2–0.3 μm under optimal cutting conditions. It should be noted that the achievable surface roughness is determined by the macroscopic tool geometry at feeds $f > 100$ μm, and by the size and shape of the cutting edge defects when $f < 50–80$ μm [6]. First, complex multi-parameter 2D and 3D analysis of the surface finish after hard turning had been done by Klocke et al. [4] and Grzesik and Wanat [7,11]. One of the fundamental findings of this research was that hard turning and grinding produce different surfaces related to the form of profile and topography structure.

Typical wear scars appearing in CBN finishing turning are shown in Fig. 2a. In this investigation surface finish represented by R_a parameter was assessed on 63 HRC AISI M50 tool steel parts in terms of cutting distance, and VB_{max} flank wear. It is concluded [12] that at a small depth of cut of 50 μm and cutting speed of 2 m/s the surface roughness was kept in the range 0.05–0.1 μm R_a at the cutting distance of 6000 m (equivalently 200 μm VB_{max}).

More recently Chou et al. [10] performed similar surface finish-tool wear (SF-TW) tests on hardened to 61–63 HRC AISI 52 100 steel specimens under finishing conditions and revealed that the transferred layer on the flank wear land of CBN tools may result in adhesion of the binder compound and significantly affect the tool wear process. The morphology of the transferred layers changed with the cutting speed. In particular, as depth of cut increases from 50 to 250 μm, flank wear rates show very minor changes. Generally, for CBN-L Ra remained below 0.4 μm for the entire 127 mm cutting length (21 min of cutting time), and VB_{max} reached about 0.25 mm [10].

Lima et al. [8] evaluated the changes of the R_a surface roughness on 58 HRC AISI D2 cold work steel parts in terms of VB_C wear indicator in turning, using mixed alumina inserts at the cutting speeds of 80, 150 and 220 m/min and three feeds of 0.05, 0.1 and 0.15 mm/rev and 1 mm depth of cut. For example, after 5 min turning test ($v_c = 150$ m/min, $f = 0.1$ mm/rev) the R_a of 0.5 μm corresponded to the wear land width of $VB_C = 0.10$ mm and after next 10 min when wear progressed to 0.18 mm the relevant R_a value increased to 0.58 μm. Kumar et al. [13] concluded after Stachowiak [14] that notch wear is mostly observed in the ceramic tools because insufficient toughness while machining hard materials. They noted that Ti(C,N) mixed ceramic (70% Al_2O_3 and 30% Ti(C,N)) tools exhibit notch wear in the range of 0.4 mm after 20 min cutting test (about 0.3 mm after 15 min) at cutting speed of 270 m/min and feed rate of 0.12 mm/rev, when machining EN 24 steel (45 HRC). As a result, R_a parameter exceeds not typical for finish HT value of 4 μm. Good performance of both Ti(C,N) mixed and zirconia toughened ceramic tools in HT is based on the balance between overall flank wear and its drastic development in the tool corner area. The flank wear has minimal effect on the surface roughness until the nose region is not severely affected by flank wear or by general tool wear, as for example crater wear. The same practical recommendation can be found in Ref. [15] where a hardened steel (HV760) was machined by ceramic tools with cutting speed of 60 m/min, feed rate of 0.1 mm/rev and 0.1 mm depth of cut. A severe deterioration of surface finish (R_{max} roughness parameter increases rapidly above 2.5 μm) begins when width of flank wear VB exceeds 0.15 mm, i.e. the cutting edge tends to get rough.

Table 1
Chemical composition and mechanical properties of hardened 40H steel (DIN 41Cr4, AISI 5140) according to Polish metallurgical standards

I. Chemical composition in %				
C	Mn	Si	Cr	Ni max
0.36–0.44	0.5–0.8	0.17–0.37	0.8–1.1	0.3

II. Mechanical properties after quenching at 850 °C with oil cooling	
Minimum hardness	50 HRC
Ultimate tensile strength (UTS)	981 MPa
Yield strength (Y)	784 MPa
Elongation A5	10%
Reduction of area at fracture Z	45%
Impact toughness I	590 kJ/m^2