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An approach to the microscopic study of wear mechanisms during hard turning with coated ceramics

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ABSTRACT

The influence of tool edge microgeometry on the wear of tool inserts made from mixed oxide ceramics is investigated. The microgeometry of ceramic inserts is described using quantifiable data, including, tool edge radius (r_n), roughness of the rake face (Ra) and tool edge roughness (sometimes called ‘tool edge sharpness’) Rt. Applied coatings affect these quantifiable data. Total force and mean temperature were measured to identify the safe operating region in which the tool edge is not chipped or damaged. The effect of tool microgeometry on wear progress for two types of mixed oxide ceramics-TiN-coated and uncoated, were compared using both macroscopic and microscopic tool wear data. A geometrical approach was used to determine the effective chip area at the chamfered tool edge. This involved mathematical modelling where the effective chip area, effective tool edge length and maximum distance between two subsequent transient surfaces were determined. The total forces were divided into cutting parts and parasitic parts, using both effective chip area and effective tool edge length. Total force division during hard machining operations with uncoated and TiN-coated ceramic inserts, enabled us to compare the effects of tool edge microgeometry on the main mechanisms of wear. Secondary wear areas at the chamfered tool edge were identified for both ceramic types. Hard machining produced abrasive wear pattern and smearing particles due to thermal load for uncoated ceramics; while it produced particles with iron content in the secondary wear area of TiN-coated ceramics.

1. Introduction

Research on tool material wear covers a wide area in the field of metal-cutting science with various themes of study. The most significant innovations in this field come from the areas of tool material development and coatings research. A second important aspect of laboratory research includes the study of tool edge design and tool edge microgeometry. A third aspect of cutting tool research is the application of advanced tool materials in innovative technologies such as hard machining and dry machining, amongst others. Cutting tools are often classified based on their geometry and tool performance, which are multifaceted terms. The areas mentioned above share a common attribute: tool edge wear. For instance, the capability of each type of tool is classified based on wear progress, which is a macroscopic concept of tool wear. However, tool edge microgeometry is a very important aspect, since it includes information such as the thickness of coatings, tool edge radius, tool edge roughness, etc. Tool edge microgeometry not only affects wear progress, but also influences the characteristic mechanisms of wear. Therefore, combining tool wear research with tool edge microgeometry will allow the classification of tool performance more precisely compared to solely relying on macroscopic concepts for this purpose.

Hard machining is an innovative technology capable of replacing grinding operations. The majority of current knowledge in this field relates to tools made from cubic boron nitride, CBN. Due to the high cost of CBN, recent research has looked at the

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Abbreviations: A_D, uncut chip area [mm^2]; A_e, effective chip area [mm^2]; a_p, depth of cut [mm]; b_n, length of chamfer [mm]; f, feed per revolution [mm]; F, total force when machining [N]; F_c, cutting force [N]; F_f, feed force [N]; F_p, passive force [N]; k_{Ae}, specific pressure [N/mm^2]; KB, width of crater [μm]; k_e, specific tool edge loading [N/mm]; KF, crater front distance [μm]; KT, crater depth [μm]; ℓ_e, effective tool edge length [mm]; P, common designation of tool plane; q, equivalent of the effective chip area; Ra, arithmetic mean value of surface roughness [μm]; r_n, tool edge radius [μm]; Rt, maximum peak to valley height of the profile [μm]; r_ε, tool nose radius [mm]; t_c, machining time [min]; VB, tool flank wear [μm]; v_c, cutting speed [m/min]; γ_b, angle of chamfer; γ_n, normal rake angle; θ, mean temperature at tool rake [°C]; κ_r, tool edge angle; λ_s, tool edge inclination angle

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applicability of ceramics in hard machining. In an attempt to replace CBN with ceramics, and test its applicability in hard machining, the objective of this paper is to determine whether there is a strong relationship between tool edge microgeometry and wear mechanisms.

2. State-of-the-art and research motivation

Hard machining is an innovative technology for machining materials of hardness between 45 and 65 HRC (447–835 HV). It has two advantages: firstly, its high precision during production; Byrne et al. [1] quote IT3-IT5 (Rz = 1–3 μm) as high precision hard machining, and IT5-IT7 (Rz = 2–4 μm) as precision hard machining. Secondly, its flexibility; according to Rech and Moisan [2] and Kundrak et al. [3], hard machining can produce a variety of surfaces. Bartarya and Choudhury [4] provide a good review on the applicability of CBN, ceramics and coated carbides as tool materials in this technology.

There are two main advantages of using ceramics in hard machining: The first is the low cost of ceramic inserts, which is about 14% of that of CBN. The second is the wide range of cutting speeds, v_c, that can be achieved. Table 1 shows that ceramics as tool materials have a wide range of cutting speeds. Table 1 also shows that similar tool performance criteria are applied.

Table 1
A literature review of ceramics used in hard machining, their hardness, cutting conditions and the relevant performance parameters that were investigated

Author(s)	Types of ceramics	Work-piece and its hardness	Cutting conditions	Ceramic tool performance parameters investigated
Aslantas et al. [5]	Al_2O_3+TiC,N	AISI 52,100, Hardness ≈ 63 HRC (775 HV)	$v_c=150–300$ m/min $f=0.07–0.14$ mm $a_p=0.5$ mm	Wear morphology, crater wear formation, EDX line analysis, roughness vs. time, tool life
Bhattacharya et al. [6]	Al_2O_3-TiO,C	DIN 100Cr6, Hardness ≈ 60 HRC (698 HV)	$v_c=130$ m/min $f=0.14$ mm $a_p=0.24$ mm	Ceramic insert surface modification, passive force F_p, EDX and XRD analysis, wear progress, wear mechanisms
Chou and Song [7]	Al_2O_3+TiC	AISI 52,100 Hardness ≈ 60–62 HRC (698–748 HV)	$v_c=120–180$ m/min $f=0.05–0.5$ mm $a_p=0.2$ mm	Forces, specific energy, effect of nose radii, white layer, modelling of the temperature distribution in front of tool edge
De Godoy and Diniz [8]	Al_2O_3+TiC Al_2O_3+SiC whiskers reinforced	AISI 4340 Hardness 56 HRC (612 HV)	$v_c=150–270$ m/min $f=0.08$ mm $a_p=0.2$ mm	Tool life, flank wear progress, SEM, EDS analysis, surface roughness vs. removal
Kumar et al. [9]	$Al_2O_3+ZrO_2$ $Al_2O_3+TiC,N+ZrO_2$ $Al_2O_3+TiN+TiC$ Al_2O_3+SiC whiskers	SS 410 Hardness HRC 60 (698 HV)	$v_c=120–270$ m/min $f=0.12$ mm $a_p=0.5$ mm	Flank wear, crater wear, notch wear, wear progress, tool life, tool failure
De Oliveira et al. [10]	Al_2O_3+SiC whiskers	AISI 4340 Hardness 56 HRC (612 HV)	$v_c=150$ m/min, $f=0.08$ mm $a_p=0.15$ mm	Tool life, flank wear progress, wear mechanisms, surface roughness vs. cutting time
Sokovic et al. [11]	Al_2O_3+TiC Al_2O_3 and coatings: TiN+TiAlSiN+TiN TiN+multi TiAlSiN+TiN TiN+TiAlSiN+AlSiTiN TiAlN TiCN+TiN Al_2O_3+TiN	Grey cast iron Hardness 260 HB (274 HV)	$v_c=200$ m/min, $f=0.15$ mm $a_p=2$ mm	Flank wear progress, flank wear comparison, surface roughness comparison, efficiency index for coating of ceramics
Grzesik [12]	Al_2O_3+TiC	Steel 40H (DIN 41Cr4, AISI 5140) Hardness 60 ± 1 HRC (698 ± 24 HV)	$v_c=100$ m/min $f=0.04–0.80$ mm $a_p=0.25$ mm	Wear at rake face and corner and secondary flank, notch wear, wear progress, surface profile
Grzesik and Malecka [13]	Si_3N_4 Al_2O_3+TiN coating	EN-GJS-500-7 Hardness HB 170 (170 HV)	$v_c=100–240$ m/min, $f=0.16$ mm $a_p=2$ mm	Flank wear progress, EDX and EDS analysis, SEM documentation, forces vs. time, forces vs. tool wear
Grzesik et al. [14]	Si_3N_4+TiN coating	EN-GJS-500-7 Hardness HB 170 (170 HV)	$v_c=100–480$ m/min, $f=0.08$ mm $a_p=0.8$ mm	Force vs. time, force vs. flank wear, confocal laser scanning of tool wear