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Optimization of geometry parameters for ceramic cutting tools in intermittent turning of hardened steel

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ABSTRACT

For the purpose of improving the ceramic cutting tool lives in intermittent hard turning, investigations on optimization of tool geometry parameters were conducted in the present study. The initial damage of the ceramic cutting tool was determined based on damage mechanics. The initial damage was more sensitive to the changes of porosity when it was relatively low. The stress distribution of the tool body was obtained using finite element simulation. The initial damage of the cutting tool and the tool stress were integrated on the basis of the concept of damage equivalent stress. The evolutions of the maximum value of damage equivalent stress on the tool body were acquired for different cutting length ratios and different combinations of tool geometry parameters. The highest value of damage equivalent stress in one cutting cycle was proposed as a new indicator for optimization of tool geometry parameters. The contribution order of tool geometry parameters for the indicator was corner radius, cutting edge angle and rake angle. This order stayed the same at different cutting length ratios. The optimization method for ceramic tool geometry parameters was proposed and it was validated through intermittent turning tests.

1. Introduction

The Al_2O_3-based ceramics have been widely used in the machining of hardened steel due to their high hardness, wear resistance and heat resistance [1,2]. It was found that the Al_2O_3-based ceramic cutting tools can be used at higher cutting speed than carbide and cermet tools [3]. In the intermittent cutting process, the mechanical and thermal impacts were fiercer. Intrinsic defects such as lower fracture toughness, lower strength and lower thermal shock resistance make the Al_2O_3-based ceramics sensitive to fracture especially in intermittent hard cutting. Since the ceramic cutting tools are more inclined to fail in intermittent hard cutting, the manufacturing cost is higher and the quality of the machined surface is poorer. Therefore, it is urgent to enhance the ceramic tool life in intermittent hard cutting. There generally exist two ways to improve the ceramic tool life. One way is to enhance the mechanical property of the Al_2O_3-based ceramic tool materials by means of whisker toughening, phase transformation toughening, particle dispersion toughening and synergistic toughening. The other is to optimize the geometry parameters of the ceramic cutting tool.

There have been a great amount of researches on toughening and strengthening of the Al_2O_3-based ceramic tool material [4–9]. Whereas, few study was performed in order to acquire the optimum geometry parameters of the ceramic tool in intermittent hard turning. Previous investigations [10,11] of ceramic cutting tool in intermittent hard turning mainly focused on the tool failure mechanisms. Zhao et al. [10] examined the failure mechanisms of an Al_2O_3/(W, Ti)C micro–nano-composite ceramic tool by means of intermittent hard turning. It was found that the tool lives were mainly determined by mechanical fatigue crack extension at relatively low cutting speed (110 m/min). When the cutting speed increased to be 170 m/min, the complex thermomechanical damage had great effects on the tool failure. Cui et al. [11] studied the failure mechanisms of Al_2O_3/(W, Ti)C ceramic tools in intermittent turning of hardened steel using damage mechanics. The influences of tool rake angle, tool clearance angle and exit angle on tool failure were analyzed.

Many of the previous researches on optimization of tool geometry parameters were conducted in the field of continuous turning [12–15] and milling [16,17]. Jawahir et al. [12] proposed a new methodology for predicting the dominant tool failure modes in turning with complex grooved tools used. The predictive model is expected to contribute greatly in the design of chip-grooves. Neşeli et al. [13] investigated the effects of tool geometry on surface roughness in turning of AISI 1040

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Nomenclature

ρ_w	density of the workpiece
E_w	Young's modulus of the workpiece
ν_w	Poisson's ratio of the workpiece
C_{pw}	specific heat of the workpiece
λ_w	thermal conductivity of the workpiece
C_R	the ratio of the cutting length to air-cutting length
t_p	the thickness of the workpiece plate
d	diameter of the workpiece
n_p	the number of the workpiece plates
ρ	density of the cutting tool
E	Young's modulus of the cutting tool
ν	Poisson's ratio of the cutting tool
C_p	specific heat of the cutting tool
Λ	thermal conductivity of the cutting tool
HV	Vickers hardness
r_c	corner radius of the cutting tool
γ_o	rake angle of the cutting tool
κ_r	cutting edge angle of the cutting tool
λ_s	inclination angle of the cutting tool
v_c	cutting speed
a_p	depth of cut
f	feed rate
$\overline{\sigma}$	shear stress
$\overline{\varepsilon}$	shear strain
$\dot{\overline{\varepsilon}}$	shear strain rate
T	absolute temperature
C	strain rate sensitivity
n	strain hardening exponent
m	thermal softening coefficient
D_i	initial damage of the cutting tool
D	damage of the tool material
RVE	representative volume element
$\boldsymbol{\sigma}$	tri-axial stress
$\boldsymbol{\sigma}_c$	uni-axial compressive stress
σ^*	damage equivalent stress
N	the number of pre-existing microcracks within the cutting tool material
E_D	Young's modulus of the material with damage
W_1	the work done by the external uni-axial compressive stress
U_e	the elastic strain energy caused by the growth of the tensile cracks
W_f	the frictional energy dissipated by the sliding of the initial microcracks
c	half the length of the initial microcrack
θ	the angle of tensile crack to initial crack
μ	the frictional coefficient
l	the length of the tensile crack
w	half of the distance between the cracks
d_g	the grain size of the ceramic tool material
f_i	area density of the initial microcracks
N_i	the number of microcracks per unit area
P_m	the porosity of the tool material
S_{DM}	the maximum value of damage equivalent stress on the tool body
F_{xi}	data points of the cutting force in X direction
F_{yi}	data points of the cutting force in Y direction
F_{zi}	data points of the cutting force in Z direction
$F_{ri.}$	data points of the resultant cutting force
F_r	the average value of the resultant cutting force in the cutting period
T_a	average values of the highest temperatures on the tool body in the cutting period
S_{DMI}	the peak value of damage equivalent stress which arose as the tool cut into the workpiece
S_{DMO}	the peak value of damage equivalent stress which arose as the tool cut out of the workpiece
S_{DMH}	the highest value of damage equivalent stress in one cutting cycle
AOM	analysis of means
ANOVA	analysis of variance
N_l	tool life

steel. A prediction model for average surface roughness was built on the basis of experimental data. The analysis results showed that the tool nose radius can be considered as the dominant factor on surface roughness. Tamizharasan and Senthil Kumar [14] made an attempt to minimize flank wear of uncoated carbide inserts in turning of AISI 1045 steel using finite element simulation. The influences of tool geometries on tool flank wear, surface roughness and cutting forces were analyzed. The optimum tool geometry was obtained and validated experimentally. Senthil Kumar and Tamizharasan [15] studied the effects of tool geometry on flank wear, surface roughness and material removal rate in turning AISI 1045 steel. Confirmation tests and finite element simulation were conducted for the optimum geometry parameters. Experimental studies were conducted by Suresh Kumar Reddy and Venkateswara Rao [16] to investigate the effects of tool geometry and cutting conditions on cutting performance in end milling of medium carbon steel. The minimum values of surface roughness and their respective optimal conditions were identified in this work. Three-dimensional finite element simulation of end milling was used by Li et al. [17] in order to optimize the tool geometry of end mill. The optimum geometrical parameters of the cutting tool were obtained in terms of cutting force and cutting temperature.

These experimental and theoretical studies on tool geometry optimization provided much valuable information. It can be found that the optimization methods depicted in these researches were proposed with cutting force, cutting temperature, macroscopic wear of the cutting tool or surface roughness as indicator. The initial state of the microstructure of tool material has great influence on the performance of the cutting tool. However, the indicators applied in the previous investigations barely reflected the initial microstructure of the cutting tool. Previous study [11] indicated that there existed initial damage within the ceramic tool material. The initial damage was greatly influenced by the initial microstructure of the tool material. Therefore, new indicator for tool geometry optimization with initial damage considered should be put forward in order to improve the ceramic tool life in intermittent cutting. Damage mechanics has become an engineering tool in the fields of aeronautics, civil engineering, nuclear power plants and the automotive industry [18]. It can be used to evaluate the response and reliability of materials weakened by randomly distributed microcracks [19]. Damage mechanics can be applied to investigate and determine the initial damage of the ceramic tool material.

The cutting tool and the workpiece interacted with each other in the cutting process, resulting in the mechanical and thermal loads which were imposed on the cutting tool. Thus, for the purpose of improving the ceramic tool life in intermittent cutting, the effects of the external loads should also be taken into account when proposing the indicator for tool geometry optimization. The distributions of tool stress reflect the impact of external loads on cutting tool. However, it is difficult to acquire the tool stress distributions by means of experiments. Finite element simulation has been extensively used in the field of metal cutting to analyze quantities difficult to obtain experimentally [20–22]. Finite element simulation offers the opportunity for quantitative analysis of tool stress.