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Reliability analysis of ceramic cutting tools in continuous and interrupted hard turning

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ABSTRACT

Reliability analysis was carried out for ceramic cutting tools used in continuous and interrupted hard turning. On the basis of micromechanics and damage mechanics, statistical characteristics of the original defects in the tool material microstructure were evaluated and analyzed. A new tool performance indicator was proposed considering the combined effects of the original damage of the tool material microstructure, the macro-mechanical properties of the tool material and the external loads on the cutting tool. Statistical analysis of the tool performance indicator was performed for continuous and interrupted turning. The relationship between tool reliability and the probability distribution of tool performance indicator was identified. It was found that the original damage of the ceramic tool material followed a weibull distribution. The probability density of the original damage decreased as the original damage increased. When interrupted turning was adopted, tool performance indicator was relatively low and the indicator decreased as cutting length ratio became smaller. The indicator followed a weibull distribution and this was invariable when turning condition changed. Relatively low shape parameter and scale parameter in probability density function of tool performance indicator appeared when the tool was tested in interrupted turning and relatively small cutting length ratio was applied. Similar to tool performance indicator, tool lives obtained under different cutting conditions also followed a weibull distribution. When turning condition varied, shape parameter and scale parameter in probability density function of tool life changed in a similar way to those parameters in probability density function of tool performance indicator. Both the probability density function of tool life and that of tool performance indicator first increased and then decreased as the independent variable increased. Shape parameter for tool performance indicator can be used in the calculation of tool reliability when the cutting length ratio in interrupted turning was relatively small.

1. Introduction

Reliability can be described as “the ability of a system to fulfill its design functions under designated operating and environmental conditions for a specified period of time” [1]. It can be deduced that the analysis of reliability is crucial to the efficient use of a system. Being an important part of the machine tools, cutting tool is considered to have substantial effects on quantities such as cutting forces, cutting temperature and the quality of the machined surface. Tool reliability greatly influences the machining efficiency and financial cost in the cutting process [2]. Therefore, it is of great importance to have thorough understanding of the tool reliability.

There have been many studies [3–10] on the reliability of cutting tools in continuous cutting. However, scant researches [2,11] on tool reliability were conducted in the field of interrupted cutting. On the basis of four approaches for tool wear evaluation in continuous turning, investigations of tool reliability were performed by Letot et al. [3]. Those four approaches were compared and analyzed to identify the optimum one. Salonitis and Kolios [4] proposed a novel reliability estimation approach for the cutting tools with advanced approximation methods used. Analysis results indicated that the method which was put forward in the study can be considered as an efficient method for estimating the cutting tool reliability. For the purpose of assessing the reliability of cutting tools, logistic regression model was established by Chen et al. [5] using vibration signals. It was found from the research that the reliability of the cutting tools can be evaluated accurately for different failure threshold. A reliability-dependent failure rate model was utilized by Wang et al. [6] in order to analyze the reliability of cutting tool. It was found from the experimental results that the model proposed in the work was satisfactory for evaluating the tool reliability.

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On the basis of cutting tool vibration signals, a proportional hazards model was constructed and utilized by Ding and He [7] to study cutting tool reliability. Experimental results validated the correctness of the approach for tool reliability analysis. Monte Carlo simulation was combined with the cutting experiments by Fan et al. [8] in order to investigate the classical and fuzzy reliability of ceramic cutting tools in continuous turning. It was found in the research that fuzzy reliability seemed to be more reasonable than classical reliability. Yin [9] studied the reliability of multi-scale particles reinforced Al_2O_3-based ceramic tools in continuous turning. The distribution model of tool life and tool reliability model were established in the research. Cutting performance of an advanced ceramic tool in continuous wet turning was investigated by Zhao [10]. Tool reliability of the ceramic cutting tool was evaluated and analyzed in the work. Unlike the studies on tool reliability in continuous cutting, relatively few investigations [2,11] of tool reliability have been conducted in the field of interrupted cutting. Studies were performed by Liu et al. [2] to estimate the fuzzy reliability for cutting tools used in milling process. A decision making model was constructed in the work to distinguish the best time when the cutting tool should be replaced. Taking both flank and face wear into account, a reliability model was proposed by Klim et al. [11] to analyze tool reliability in variable feed milling of 17-4PH stainless steel. It was concluded in the research that the proposed method can be applied to analyze tool life for different equipments, materials and cutting conditions.

These former researches provided much valuable information for the analysis of tool reliability in cutting process. It can be found from these studies that most of the previous works on cutting tool reliability were conducted based on a considerable number of cutting tests. The experimental values of tool lives were investigated directly or indirectly in the tool reliability analysis. The finial tool failure was mainly dominated by the physical mechanisms in the cutting process. However, very few researches on tool reliability were carried out with the relationship between physical mechanisms and the final tool failure considered.

Compared to continuous cutting, the mechanical and thermal impact are relatively severe in interrupted cutting. Because of this, the cutting tools which have certain macro and micro-mechanical properties are more inclined to fracture. Taking the physical process of tool fracture into account, not only the micro-mechanical properties and macro-mechanical properties of the tool material but also the external loads applied on the cutting tool should be considered at the same time when analyzing the tool reliability in interrupted cutting. Damage mechanics is often used in order to study the response of materials weakened by randomly distributed microcracks [12]. Damage mechanics can be used as a bridge between microscopic damage and macroscopic fracture of the tool material. In the investigations of metal cutting, finite element simulation has been extensively

Table 1
Material properties of the ceramic cutting tool.

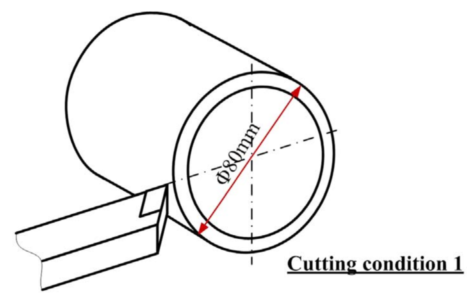
Density ρ (Kg/m^3)	Elastic modulus E (GPa)	Poisson's ratio ν	Specific heat C_p (J Kg^{-1} K^{-1})	Thermal conductivity λ (W m^{-1} K^{-1})
4100	426	0.26	860	8.25

Table 2
Material properties of the workpiece.

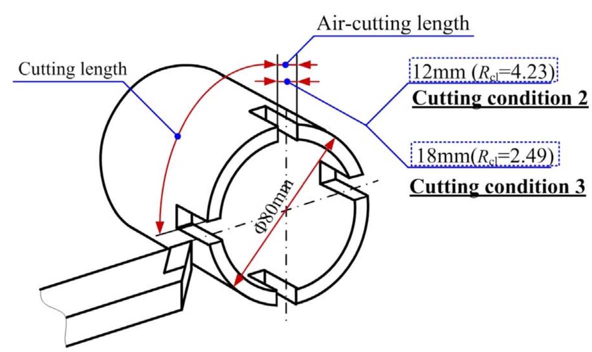
Density ρ_w (Kg/m^3)	Elastic modulus E_w (MPa)	Poisson's ratio ν_w	Specific heat C_{pw} (J Kg^{-1} K^{-1})	Thermal conductivity λ_w (W m^{-1} K^{-1})
7800	200	0.3	474	55

Table 3
Material constants for AISI 1045 steel.

A (MPa)	B (MPa)	$\dot{\varepsilon}_0$ (1/s)	n	m	C
553.1	600.8	0.001	0.234	1	0.0134

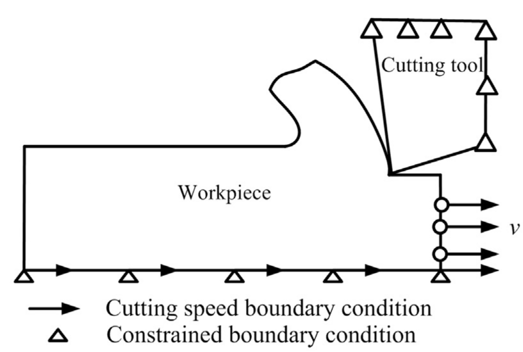


(a) Continuous turning

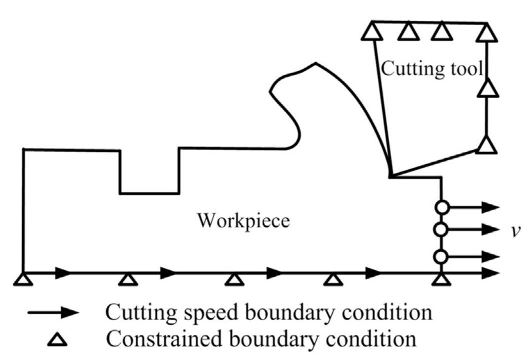


(b) Interrupted turning

Fig. 1. Cutting conditions studied in the present work.



(a) The typical schematic of finite element simulation for continuous turning



(b) The typical schematic of finite element simulation for interrupted turning

Fig. 2. The typical schematic of finite element simulation for continuous and interrupted turning.