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# Performance optimization for cemented carbide tool in high-speed milling of hardened steel with initial microstructure considered

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ABSTRACT

Investigation on cutting parameter optimization was performed to enhance the cemented carbide tool life in high-speed milling of hardened steel. Image analysis of the tool material microstructure was conducted to determine the average grain diameter and the size of the representative element. The initial state of the tool material microstructure was evaluated based on micromechanics and damage mechanics. Finite element simulation of the milling process was performed to acquire the tool stress. The original damage of the tool and simulated tool stress were integrated based on the concept of damage equivalent stress. Distribution and evolution of the damage equivalent stress on the tool body was analyzed and a new indicator for cutting parameter optimization was brought forward. A cutting parameter optimization method was proposed on the basis of the new indicator. Experimental tests showed that the proposed optimization method can be used to identify the optimum cutting parameter combination and prolong the cemented carbide tool life in high-speed milling process.



## 1. Introduction

In 1931, the concept of high-speed cutting (HSC) was first proposed by Salomon using milling tests [1]. Being a typical intermittent cutting process, high-speed milling has been extensively applied in the manufacturing of aluminum aeronautical and automotive components in order to generate surfaces with high geometric accuracy. The mechanical and thermal impacts have great influence on the tool life in high-speed milling. According to the previous researches [2,3], because of the severer mechanical and thermal impacts, fracture contributed substantially to the final failure of the cutting tool at relatively high cutting speed. Tool fracture is closely related to the initial microstructure of the tool material [4]. The initial damage of the tool material has great influence on the final fracture of the cutting tool and it should be paid attention to. The cutting tools used in the cutting process usually have initial micro-defects inside the tool material and they withstand the mechanical and thermal loads resulted from the interaction between the cutting tool and the workpiece [5]. Therefore, it can be deduced that tool fracture was greatly influenced by the combined effects of initial micro-defects within the tool material and the external loads which arose in the cutting process.

Optimization of cutting parameter is considered as an effective method to improve the tool life and a great amount of valuable studies [6–8] have been conducted in this field. However, previous researches mainly focused on the final macro failure of the cutting tool. Few studies were performed with the combined effects of initial tool microstructure and the external loads considered. It can also be found from previous researches that the optimization methods were usually conducted on the basis of numerous experimental results.

WC–Co carbides have been widely used as cutting tool in the machining of hard-to-machine materials. The microstructure parameters of cemented carbide tool greatly influenced its performance in the cutting process. For the purpose of improving the cemented carbide tool life in high-speed milling of hardened steel, research on optimization of cutting parameters is performed in the present work. The critical microstructure parameters are determined by means of image analysis. The initial state of the micro-defects within the tool material is evaluated using micromechanics and continuum damage mechanics. The original damage of the cutting tool and the tool stress acquired from finite element simulation are integrated based on the concept of damage equivalent stress. The distribution and evolution of damage equivalent stress on the cutting tool are analyzed to define the indicator for cutting parameter optimization. An optimization method for cutting parameters in high-speed milling was proposed without cutting experiments on the basis of Taguchi method. High-speed milling tests are performed to demonstrate the optimization method.

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## 2. Experimental procedures and finite element simulation

### 2.1. Cutting inserts and workpiece material

Cemented carbide tool was used in the present study. Tool holder with axial rake angle $\gamma_p = -6°$, radial rake angle $\gamma_f = -7°$, major cutting edge angle $\kappa_r = 75°$ and a tool diameter $d_t = 63$ mm was applied in the milling tests. A block of AISI H13 hardened steel (46–47 HRC) was utilized as the workpiece. All the milling tests were performed on a vertical CNC machining center under dry conditions as shown in Fig. 1(a). Properties of the cutting tool and the workpiece are shown in Table 1.

### 2.2. Cutting tests

Up milling was recommended by the tool company because it was beneficial to the acquisition of relatively long tool life. Therefore, up milling was used for most of the cutting conditions. A special design of orthogonal array is used by the Taguchi method in order to analyze the entire parameters space with a small number of tests conducted [9]. The Taguchi method was employed and the three levels of the influencing factors are shown in Table 2. The axial depth of cut ($a_p$) was fixed as 0.3 mm. Nine different combinations of cutting parameters are listed in Table 3 on the basis of Table 2. Each test was replicated three times. The cutting forces were measured using a Kistler piezoelectric dynamometer as shown in Fig. 1(a) and the sampling frequency was set to be 10000 Hz. The tool life was recorded in terms of cutting cycles when excessive chipping or catastrophic fracture arose. The initial tool material and the worn cutting tools were observed by means of digital microscope (IMPC, China) and scanning electron microscopy (SEM) (JSM-6510LV, Japan).

### 2.3. Finite element simulation

Finite element simulation has been extensively used by the researchers to acquire quantities which are difficult to obtain experimentally. Lagrangian formulation embedded in the Deform 3D package was used for the acquisition of tool stress. Simulation was conducted for each cutting condition listed in Table 3. For the purpose of improving the simulation efficiency, the workpiece geometry was simplified as shown in Fig. 1(b). The boundary conditions of the cutting tool and the workpiece were set to be consistent with those in the milling tests. Tetrahedron elements were employed to mesh the cutting tool and the workpiece. The mesh of the section where the cutting tool contacted with the workpiece was refined for the cutting tool. The mesh density in the refined section was about 150 times the mesh density in the other sections of the cutting tool. The cutting tool was modeled as elastic and heat transfer body. Local refining technology and re-meshing technology were applied in the meshing of the workpiece. The Johnson–Cook constitutive equation was used to model the deformation behavior of the workpiece. It can be expressed as:

$$\bar{\sigma} = \left[A + B(\bar{\varepsilon})^n\right]\left[1 + C\ln(\dot{\bar{\varepsilon}}/\dot{\bar{\varepsilon}}_0)\right]\left[1 - \left(\frac{T_a - T_r}{T_m - T_r}\right)^m\right] \quad (1)$$

where $\bar{\varepsilon}$, $\dot{\bar{\varepsilon}}$, $T_a$ and $\bar{\sigma}$ are the shear strain, shear strain rate, absolute temperature and shear stress, respectively. The material properties of the workpiece are dominated by the parameters such as the yield strength $A$, the hardening modulus $B$, the strain rate sensitivity $C$, the strain hardening exponent $n$, the thermal softening coefficient $m$, the

**Table 1**
Material properties of the cutting tool and the workpiece.

| | Density ($10^3$ Kg m$^{-3}$) | Young's Modulus (GPa) | Poisson ratio | Thermal conductivity (W m$^{-1}$ K$^{-1}$) | Thermal expansion ($10^{-6}$ K$^{-1}$) |
|---|---|---|---|---|---|
| Cutting tool | 14.40 | 582 | 0.21 | 74.20 | 4.50 |
| Workpiece | 7.78 | 208 | 0.27 | 28.40 | 10.40 |

**Table 2**
Factors and selected levels in the milling test.

| Factor | Cutting parameter | Unit | Level 1 | Level 2 | Level 3 |
|---|---|---|---|---|---|
| A | Cutting speed ($v$) | m/min | 300 | 600 | 900 |
| B | Radial depth of cut ($a_e$) | mm | 5 | 10 | 15 |
| C | Feed per tooth ($f_z$) | mm/z | 0.08 | 0.16 | 0.24 |

**Table 3**
Experimental layout designed based on the factors and levels listed in Table 2.

| Exp. No. | A ($v$) | B ($a_e$) | C ($f_z$) | D (error) | |
|---|---|---|---|---|---|
| 1 | 1 | 1 | 1 | | Up milling |
| 2 | 1 | 2 | 2 | | |
| 3 | 1 | 3 | 3 | | |
| 4 | 2 | 1 | 2 | | |
| 5 | 2 | 2 | 3 | | Up milling, down milling and symmetric milling |
| 6 | 2 | 3 | 1 | | Up milling |
| 7 | 3 | 1 | 3 | | |
| 8 | 3 | 2 | 1 | | |
| 9 | 3 | 3 | 2 | | |

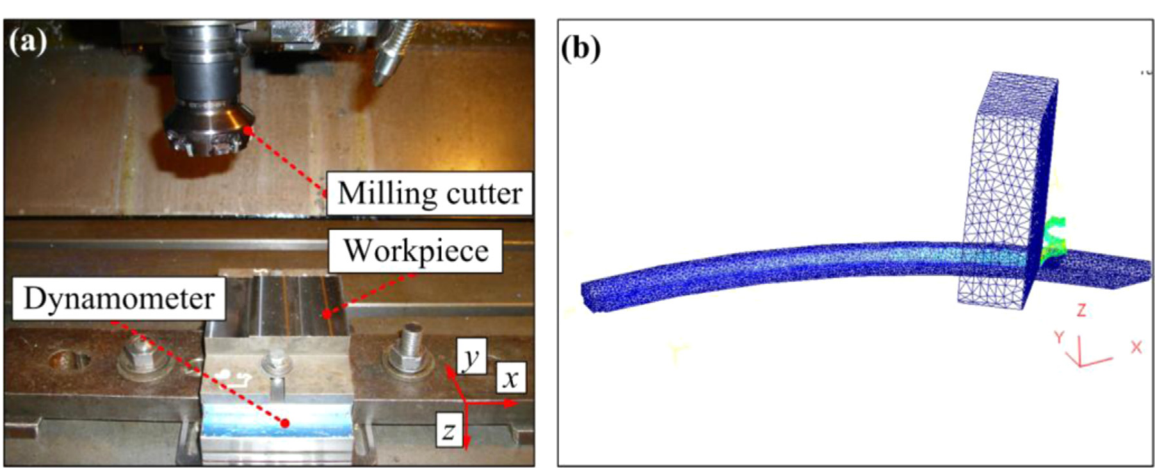


**Fig. 1.** Milling tests and finite element simulation. (a) Experimental setup. (b) Schematic of finite element simulation.