Tool Life Prediction for Ceramic Tools in Intermittent Turning of Hardened Steel Based on Damage Evolution Model

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Tool Life Prediction for Ceramic Tools in Intermittent Turning of Hardened Steel Based on Damage Evolution Model

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Abstract. Al₂O₃-based ceramic is one of the most widely used materials for tools employed in hardened steel turning applications due to its high hardness, wear resistance, heat resistance and chemical stability. The objective of this work is to predict the lives of Al₂O₃-(W, Ti)C ceramic tools in intermittent turning of hardened AISI 1045 steel by means of damage evolution model taking into account the mechanical loading and thermal effect in the cutting process. A damage evolution model analyzing the RVE with uniformly distributed interacting cracks is constructed based on micromechanics. The calculated results of the proposed damage evolution model are compared with the lives of two kinds of Al₂O₃-(W, Ti)C ceramic tools obtained through experiments. It is found that the proposed model can be used to predict the lives of the ceramic cutting tools in intermittent turning operation.

1. Introduction

The investigation and understanding of tool failure in intermittent turning process is essential for proper application and material design of different cutting tool materials. Many studies on tool failure of CBN and cemented carbide turning tools have been conducted in intermittent hard turning [1-5]. These studies concentrated on the effects of tool material content, cutting parameters and frequency of interruption. As one of the most suitable tool materials for machining hardened steels, Al₂O₃-based ceramics possess high hardness, wear resistance, heat resistance and chemical stability, with less deformation and dissolution in cutting processes. However, there are relatively few investigations of the failure of Al₂O₃-based ceramic tools in intermittent turning [6, 7]. These investigations were limited to the qualitative analysis of the observed experimental results especially the final tool failure morphology.

In the present paper, an attempt is made to apply damage mechanics to predict the lives of Al₂O₃-(W, Ti)C ceramic tools in intermittent turning of hardened AISI 1045 steel quantitatively. Because of the complex failure process of cutting tools, it is very difficult to predict tool failure directly using damage mechanics. Therefore, a damage evolution model which correlates cutting forces with cutting parameters is constructed to predict the lives and failure process of the cutting tools. The calculated results of the damage evolution model are compared with the lives of two kinds of Al₂O₃-(W, Ti)C ceramic tools in intermittent turning experiments.

2. Damage evolution model
For the intermittent turning condition shown in figure 1, a representative volume element (RVE) for the ceramic cutting tool is modelled with physical behaviour considered. It can be seen from figure 1 that the intermittent turning process constitute cutting cycles and non-cutting cycles. Therefore, the constructed RVE is under square-wave loading condition. Each time of loading is considered to be one time of impact. A damage evolution model for the RVE is about to be established to identify the trend of the damage evolution process which is correlated with the failure process of the cutting tools.

Figure 1. Workpiece and fixture geometry in intermittent turning experiment.

2.1. Simplification of the stress state of the RVE.
In the present study, the RVE is defined as a cube under tri-axial stress state, with a length \( m \) on each side. The stress state is assumed to stay the same in each impact.

Taking the quasi-unilateral condition of microdefects closure into consideration, the damage equivalent stress can be expressed as [8]:

\[
\sigma^* = \left( \frac{1 + \nu}{1 - \nu} \sigma : \sigma - \nu (\mathbf{tr} \sigma)^2 \right) + \frac{D}{1 - hD} \left( \frac{1 + \nu}{1 - \nu} \left( \sigma : \sigma - \nu (\mathbf{tr} \sigma)^2 \right) \right)^{1/2}
\]
(1)

where \( \sigma^* \) is the damage equivalent stress, \( \sigma \) is the tri-axial stress of the RVE, \( \nu \) is the Poisson’s ratio of the cutting tool material, \( D \) is the damage value of the RVE and \( h \) is on the order of 0.2. When the stress state of the RVE is pure compression, the damage equivalent stress is:

\[
\sigma^* = \left( \frac{1 - D}{1 - hD} \right)^{1/2} |\sigma_c|
\]
(2)

where \( \sigma_c \) is the pure compressive stress. \( \sigma_c \) is expressed as:

\[
\sigma_c = \begin{pmatrix}
\sigma_{11} \\
\sigma_{22}
\end{pmatrix} = \begin{pmatrix}
-\sigma_c & 0 \\
0 & 0
\end{pmatrix}
\]
(3)

where \( \sigma_{\alpha\beta} (\alpha, \beta = 1, 2) \) are stress components.

By substituting equation (2) into (1), the magnitude of \( \sigma_c \) can be derived as:

\[
|\sigma_c| = \left( \frac{1 + \nu}{1 - \nu} \sigma : \sigma - \nu (\mathbf{tr} \sigma)^2 \right) + \frac{D}{1 - hD} \left( \frac{1 + \nu}{1 - \nu} \left( \sigma : \sigma - \nu (\mathbf{tr} \sigma)^2 \right) \right)^{1/2}
\]
\[
\left( \frac{1 - D}{1 - hD} \right)^{1/2}
\]
(4)

Then the tri-axial stress \( \sigma \) of the RVE can be simplified to a uni-axial compressive stress \( \sigma_c \).

By the concept of damage equivalent stress [8], the tri-axial stress state of the RVE with certain damage value is simplified to a uni-axial compressive loading condition, both of which give the same amount of elastic strain energy. It is assumed that the calculated uni-axial compressive stress state and
the actual tri-axial stress state have approximately the same effect on the damage evolution process of the RVE.

2.2. Damage evolution of the RVE.

The RVE subjected to tri-axial stress $\sigma$ can be transformed to a material element under uni-axial compressive stress $\sigma_c$. The material element is assumed to contain pre-existing uniformly distributed interacting sliding microcracks.

There exist many micro-mechanics based models analyzing crack growth of brittle material under compression, of which the sliding crack model is widely used [9-21]. The sliding crack model is chosen to study the damage of the material element under uni-axial compressive stress. In the present study, the sliding crack model for individual microcrack is shown in figure 2 in which the crack grows along the direction of maximum axial compressive stress. The length of the initial microcrack is assumed to be $2c$, and the length of the tensile crack is $l$, oriented at an angle $\theta$ to the initial microcrack. Taking into account the interacting effects of the cracks distributed in the material element [15, 18, 21], a sliding crack model with an array of sliding microcracks under pure compression is constructed as shown in figure 3.

![Figure 2. Sliding crack model for individual microcrack.](image)

![Figure 3. Sliding crack model for the material element.](image)

According to the study by Ravichandran G and Chen W [17], the total strains of the material element under uni-axial compressive stress at the end of the $n_{th}$ impact can be written as:

$$\begin{pmatrix} e_1 \\ e_2 \end{pmatrix} = \begin{pmatrix} e_1^e + e_1^d \\ e_2^e + e_2^d \end{pmatrix} = \frac{(\kappa+1)(\nu+1)}{4E} \begin{bmatrix} \frac{\kappa-3}{\kappa+1} \\ 1 \end{bmatrix} \begin{pmatrix} \sigma_c \\ 0 \end{pmatrix} + N \begin{bmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{bmatrix} \begin{pmatrix} \sigma_c \\ 0 \end{pmatrix}$$

where $e_1^e$ and $e_2^e$ are elastic strains associated with tool material without damage, $e_1^d$ and $e_2^d$ are damage strains for the material element caused by the sliding of initial microcracks and the growth of the sliding cracks, $E$ and $\nu$ are the Young’s modulus and Poisson’s ratio of the cutting tool material, $N$ is the number of the pre-existing microcracks in the material element, $S_{\alpha\beta}$ $(\alpha, \beta = 1, 2)$ are constants, and $\kappa = 3-4\nu$, $\kappa = [(3-\nu)/(1+\nu)]$ are for plane strain condition and plane stress condition respectively.

With $e_i = c_i$, it can be obtained that:
\[ \sigma_c = \frac{E}{1 + ENS_{11}} \epsilon \quad (6) \]

The degradation of the Young’s modulus of the damaged material can be used to define the damage \( D \) of the material element.

\[ \sigma_c = E\epsilon = E(1 \cdot D)\epsilon \quad (7) \]

Therefore, at the end of the \( n_{th} \) impact, the damage induced by uni-axial compressive stress of the material element can be expressed as:

\[ D = 1 - \frac{1}{1 + ENS_{11}} \quad (8) \]

The energy equilibrium equation of a body with one single sliding crack under compression is [14]:

\[ 2U_e + W_f = W_l \quad (9) \]

where \( U_e \) is the elastic strain energy resulted from the growth of the tensile cracks, \( W_f \) is the frictional energy dissipated by the sliding of the initial microcrack and \( W_l \) is the work done by the applied uni-axial compressive stress.

Based on equation (9), \( S_{11} \) can be obtained as:

\[ S_{11} = \frac{1}{4ab} \left( \frac{k+1}{k+1} \right) \left( \frac{C_i - l_n}{C_i - 0.75\ell_0} \right) \frac{2}{E} \frac{1}{\pi} \ln \frac{\tan \frac{\pi}{2w} \left( l_n + \ell' \right)}{\tan \frac{\pi}{2w} \left( \ell_n \right)} \]

\[ + \frac{1}{4ab} \epsilon \mu (1 - \cos 2\theta) \left( \frac{k+1}{k+1} \right) \frac{2}{E \sin \theta} \left[ \sin 2\theta - c \mu (1 - \cos 2\theta) \right] \frac{w \sin \frac{\pi}{2w} \left( l_n + \ell' \right)}{w} \left[ 2 \pi \left( l_n + \ell' \right) \right]^{-1/2} \quad (10) \]

where \( 4ab \) is the area of the material element, \( C_i \) is the Rayleigh wave speed of the material under consideration, \( l_n \) is the crack growth velocity during the \( n_{th} \) impact which is assumed to remain constant, \( \epsilon \) is half the length of the initial microcrack, \( \mu \) is the frictional coefficient, \( l_n \) is the crack length at the end of the \( n_{th} \) impact, \( \ell' = 0.27c \) [21], \( \ell'' = 0.083c \) [16].

\( l_n \) can be expressed as:

\[ l_n = l_{n-1} + l_n \Delta t \quad (11) \]

where \( \Delta t \) is the time each impact cost, \( l_{n-1} \) is the crack length at the end of \((n-1)_{th}\) impact.

\( l_n \) must be predetermined to calculate the damage value of the RVE at the end of the \( n_{th} \) impact through equation (8). In order to build the relationship between calculated results of the damage evolution model and the cutting tool lives, an empirical formula of \( l_n \) is constructed. During cutting process especially high speed cutting process, the temperature on the tools has remarkable effect on tool failure. Taking into account the thermal influence on crack growth velocity, \( l_n \) is constructed as:

\[ l_n = C_i \left( \frac{K_i - \alpha K_{ic}}{K_i - \beta K_{ic}} \right) \left( \frac{V_c}{V_i} \right)^{\gamma} \quad (1 > \alpha > \beta) \quad (12) \]
where $K_1$ is the stress intensity factor at the beginning of the $n_{th}$ cut, $K_{IC}$ is the fracture toughness of the cutting tool material, $\gamma$ is a constant defined to guarantee that the magnitude of $l_n$ is suitable for the calculation of the model, and $V_c$ is the cutting speed. As cutting speed affect the tool temperature most significantly among all the cutting parameters (cutting speed, depth of cut, feed rate), a certain cutting speed $V_s$ is chosen as a benchmark. And the $\lambda$th power of the ratio of $V_c$ to $V_s$ is used to reflect the tool temperature effect.

For the purpose of calculability and engineering application, $K_1$ is correlated with the cutting forces which can be obtained through intermittent turning experiments. $F_x$, $F_y$ and $F_z$ are used to represent the mean value of axial cutting force, radial cutting force and tangential cutting force in the cutting cycle respectively.

The parameters in equation (12) will be obtained through experiments. From equation (12), it can be easily seen that with the increment of the stress intensity factor and the cutting speed, the crack growth velocity grows. And when $K_{IC}$ increase the crack growth velocity will decrease.

In order to identify the failure onset of the material element, the critical damage value should be defined. In equation (8), the crack growth velocity $l_n$ is assumed to be infinite and the crack length $l_n$ is replaced by $2w$ which is the distance between the cracks, then the calculated damage value is considered to be the critical damage value $D_c$ for the failure of material element. When the damage value $D$ surpasses $D_c$, the impact number is recorded and multiplied by a correction factor $M$ which is affected by the standard cutting speed $V_s$, so that the cutting tool life (in number of impacts) can be obtained.

$D_0$, $l_0$, and $l_0$ are the initial damage of the material element, the initial length of the tensile crack and the initial crack growth velocity respectively. The initial conditions for the calculation of the damage evolution model are assumed to be: $D_0=0$, $l_0=0$, and $l_0=0$. After $n$ times of impact, the damage of the material element is $D_n$ and the crack length is $l_n$. Damage $D_n$ and crack length $l_n$ are the initial conditions for the $(n+1)_{th}$ impact. Before the beginning of the $(n+1)_{th}$ impact the crack growth velocity is considered to be zero.

![Figure 4. A schematic of tool wear.](image-url)
Figure 4 shows the schematic of tool wear. VB is the flank wear width. Flank wear value VB of 0.3 mm is usually used as the tool life criterion. As for the prediction of failure process of the ceramic cutting tools in intermittent turning, the relationship between the damage value of the RVE during the damage evolution process and the predicted flank wear value of the cutting tools is established as shown in equation (14):

\[
\begin{align*}
  n_T &= Mn \\
  VB(n_T) &= \frac{0.3}{D_f} D_n
\end{align*}
\]

(14)

where \(n_T\) and \(n\) are the number of impacts that the ceramic cutting tools and the RVE undertake respectively, \(D_f\) is the calculated damage value when the RVE fails, \(D_n\) is the calculated damage value of the RVE after \(n\) times of impacts, and \(VB(n_T)\) is the predicted flank wear value of the ceramic cutting tools after \(n_T\) times of impacts.

3. Comparison with experimental results

To determine the parameters in equation (12) and the correction factor \(M\) in equation (14), intermittent turning operations were conducted using \(\text{Al}_2\text{O}_3\)-based ceramic tools with different fracture toughness. The intermittent turning operations were conducted on a CA6140 lathe under dry conditions. The workpiece materials were in the form of four 16 mm thick plates clamped in the straight slots which were peripherally and uniformly distributed on a cylindrical fixture as shown in figure 1. Programming calculation is conducted to compare the experimental results with the calculated results so as to obtain the accurate values of the parameters. As the \(\text{Al}_2\text{O}_3\)-based ceramic tools under consideration have similar microstructure, it is assumed that they have the same critical damage \(D_c\). Different combinations of the values of the parameters \((\alpha, \beta, \gamma, \text{and } \lambda)\) are programmed. The ratios of the experimental results to the calculated results under different cutting conditions can be obtained. The combination that leads to the minimum variation of the ratios is considered to be suitable for tool life prediction. And the mean value of the ratios is determined as the correction factor \(M\). The calculated results of the programm are \(\alpha=0.25, \beta=0.1875, \gamma=10^{-9}, \lambda=2, M=280 (V=113 \text{ m/min})\).

As can be seen from equation (12), under the same cutting parameters, life variation of different tools is mainly caused by the difference of fracture toughness. Since the programming calculation has taken the difference of tool fracture toughness into consideration, one set of parameters can be used to predict the lives of different \(\text{Al}_2\text{O}_3\)-based ceramic tools.

To validate the proposed damage evolution model, orthogonal intermittent turning tests were carried out under the same condition as is illustrated in figure 1 using two kinds of \(\text{Al}_2\text{O}_3\)-(W, Ti)C microcomposite ceramic tools (SG-4 and AWT-10). SG-4 is a commercially available \(\text{Al}_2\text{O}_3\)/(W, Ti)C microcomposite ceramic tool. And AWT-10 is a kind of \(\text{Al}_2\text{O}_3\)/(W, Ti)C micro-nano-composite ceramic tool. The material of the workpiece was hardened AISI 1045 steel (44-48 HRC). The cutting parameters of orthogonal experiments are shown in table 1. The properties of the cutting tools are listed in table 2. All of the cutting tools were fabricated to have 0.1 mm × (-15º) chamfer and 0.3 mm corner radius. Cutting geometry was 45º cutting edge angles, -8º rake angle, and 0º clearance angle. The insert type was SNMN 150404. The condition of the cutting edge was examined periodically with an optical microscope, and the change of flank wear value was recorded. Flank wear value of 0.3 mm was used as the tool life criterion. Under given machining conditions each experiment was replicated five times. The cutting forces were measured using a signal acquiring system with a force sensor of Kistler 9441 and a three-channel charge amplifier of Kistler 5807A at the very beginning of each experiment. Comparisons of tool lives obtained through experiments and the damage evolution model are shown in table 3. The longer tool life of AWT-10 is attributed to its synergistic strengthening/toughing mechanism induced by the (W, Ti)C microparticles and \(\text{Al}_2\text{O}_3\) nanoparticles. The average deviations between the experimental results and the calculated results by the modified damage evolution model are 4.3% and 4.6% for SG-4 and AWT-10 respectively.
Table 1. Cutting parameters of orthogonal experiments.

| Exp. No. | Cutting speed $V_c$ (m/min) | Depth of cut $a_p$ (mm) | Feed rate $f$ (mm/r) |
|----------|----------------------------|------------------------|---------------------|
| 1        | 113                        | 0.10                   | 0.10                |
| 2        | 113                        | 0.15                   | 0.15                |
| 3        | 113                        | 0.20                   | 0.20                |
| 4        | 158                        | 0.10                   | 0.15                |
| 5        | 158                        | 0.15                   | 0.20                |
| 6        | 158                        | 0.20                   | 0.10                |
| 7        | 188                        | 0.10                   | 0.20                |
| 8        | 188                        | 0.15                   | 0.10                |
| 9        | 188                        | 0.20                   | 0.15                |

Table 2. Properties of the tool materials.

| Tools   | Flexural strength $\sigma_f$ (MPa) | Fracture toughness $K_{IC}$ (MPa m$^{1/2}$) | Vicker’s hardness $HV$ (GPa) | Passion ratio $\nu$ | Density $\rho$ (Kg/m$^3$) | Young’s modulus $E$ (GPa) |
|---------|----------------------------------|---------------------------------------------|-----------------------------|-------------------|----------------------------|--------------------------|
| SG-4    | 870                              | 5.15                                        | 21.7                        | 0.23              | 6500                       | 436                      |
| AWT-10  | 930                              | 7.55                                        | 23.5                        | 0.23              | 6460                       | 469                      |

Table 3. Comparison of tools lives (in number of impacts) obtained via orthogonal experiments and calculation of the damage evolution model.

| Exp. No. | SG-4 (Experimental) | SG-4 (Calculated) | Deviation | AWT-10 (Experimental) | AWT-10 (Calculated) | Deviation |
|----------|---------------------|-------------------|-----------|----------------------|---------------------|-----------|
| 1        | 30000               | 29400             | 2.0%      | 37000                | 36400               | 1.6%      |
| 2        | 28000               | 27440             | 2.0%      | 32000                | 29400               | 8.1%      |
| 3        | 25000               | 26600             | 6.4%      | 28600                | 27720               | 3.1%      |
| 4        | 20080               | 19880             | 1.0%      | 23700                | 22120               | 6.7%      |
| 5        | 18600               | 19320             | 3.9%      | 22000                | 20160               | 8.4%      |
| 6        | 19200               | 19880             | 3.5%      | 22900                | 21560               | 5.6%      |
| 7        | 16800               | 17640             | 5.0%      | 21000                | 21280               | 1.3%      |
| 8        | 17600               | 17360             | 1.4%      | 20400                | 20720               | 1.6%      |
| 9        | 14800               | 16800             | 13.5%     | 17300                | 18200               | 5.2%      |

As is shown in figure 5, the tool failure processes obtained through experiments and the damage evolution model are compared. It can be seen from figure 5 that although the results obtained by the model can not predict the failure process with a high accuracy, they have similar trend with those obtained through experiments. The predicted results have relatively high accuracy in the early stage of
tool failure process. In the middle stage, compared with the experimental results the predicted value of tool wear increase more slowly, which is opposite in the late stage.

![Comparison of tool failure process](image)

**Figure 5.** Comparison of the tool failure process obtained by experiment and calculation of the damage evolution model. (The experiment was tested at $V_c=188\, \text{m/min}$, $f=0.15\, \text{mm/r}$ and $a_p=0.1\, \text{mm}$ using SG-4 and AWT-10 ceramic cutting tool.)

4. Conclusions

An attempt is made to predict the Al$_2$O$_3$-(W, Ti)C ceramic cutting tools lives in intermittent turning of hardened AISI 1045 steel by means of damage evolution model. A RVE for the cutting tool with uniformly distributed interacting cracks is constructed taking into account the physical behaviour of the cutting tool based on micromechanics. The complex tri-axial stress state of the RVE is simplified to a uni-axial loading condition by the concept of equivalent damage stress in continuum damage mechanics (CDM). A damage evolution model analyzing the RVE is established, which correlates the cutting forces with cutting speed. An empirical formula of crack growth velocity is constructed to build the relation between the calculated results of the damage evolution model and the experimental results.

The proposed damage evolution model is validated by orthogonal intermittent turning experiments of hardened AISI 1045 steel, with two kinds of Al$_2$O$_3$-(W, Ti)C ceramic tools used. It is found that the calculated results of the modified damage evolution model have good agreement with the experimental ones. The failure process of the ceramic cutting tools obtained through the proposed model have similar trend with that obtained through experiments. It is found that the damage evolution process calculated through the damage evolution model can be used to predict the lives and failure process of the ceramic cutting tools in intermittent turning of hardened AISI 1045 steel.

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