Wear Mechanism of Cemented Carbide Tool and Modeling Tool Wear in Machining Inconel 718

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Abstracts: When machining Inconel 718, tool wear is a serious problem, which affects the quality of the workpiece. In order to analyze the wear mechanism in dry machining Inconel 718 with cemented carbide tool, the wear morphology of the tool was observed by CCD and scanning electron microscopy (SEM) equipped with energy dispersive X-ray spectrometer in this paper. The results showed that at low cutting speed, the formation and shedding of the built-up-edge caused severe cutting tool breakage. When the cutting speed reached 40 m/min, the tool material fell off from the tool substrate in the form of wear debris, which was the main reason for tool wear. In addition, the elements diffusion between the tool and the workpiece and oxidation reaction accelerated the formation and falling off of wear debris. According to the tool wear mechanism, a tool wear prediction model was established. In machining Inconel 718, the excellent experimental agreement have been obtained in the prediction of wear in cemented carbide tool.

1. Introduction

Inconel 718 is a kind of nickel based super alloy with high oxidation resistance, corrosion resistance, high temperature resistance and other unique properties. It is widely used in the aerospace industries, marine, pollution control equipment and other industries, due to its high mechanical strength even in extreme environment. However, Inconel 718 is considered as a “difficult-to-cut super alloy”, owing to its characteristics of poor thermal conductivity, high cutting temperature, large cutting force, high toughness and serious tool wear, which poses several problems when machining the material [1].

In order to improve the machinability of Inconel 718, the scholars have studied the effects of cutting parameters, including different cutting speeds, feed rate, coating materials, thermally activated mechanism, machining strategy and so on, on the wear of tools. Nalbant et al. have claimed that there is a negative relationship between cutting speed and main cutting force, the main cutting force decreased with the increased cutting speed [2]. Liao and Shiue have found that the Ni or Fe elements in the workpiece diffused into the tool binding layer (Co) in turning of Inconel 718 under the condition of high speed turning \((v_c=35\ m/min)\), which weakened the bond strength between carbide particles (WC, TiC, TaC) and binder (Co) [3]. Under the action of high flow stress, cemented carbide particles are separated from cemented carbide tools, which produced wear on the cemented carbide tools.
Kitagawa et al. have proposed that the wear of ceramic tools in machining Inconel 718 is caused by abrasive process, but not the thermal activation mechanism [4]. They used ceramic tools to machine Inconel 718 alloy, and found that variation of the chip formation mechanism from continuous to discontinuous caused severe boundary notch wear on the ceramic tools. The tool wear on the machined surface is also affected by the heat generation and the plastic deformation induced during machining [5]. Thakur et al. have proved that the tools would deform plastically at the cutting edge of the tools due to the higher temperature caused by the increased cutting speed and feed rate [6].

The coated carbide tools are widely used in the field of metal cutting because of their high hardness, high wear resistance, good chemical stability and high versatility. Devillez et al. have proposed that the AlTiN coating is the suitable coating material in dry machining condition for Inconel 718 [7]. On the surface of tool in machining of Inconel 718, the work materials adhere to the cutting edge to form a built-up-edge and a built-up-layer, which are not always stable. Depending on cutting conditions and on used tool, the pieces of attached working materials are removed, which can drop out to tool particles causing craters on front face. Hao et al. have optimized the processing temperature for PVD-coated (TiAlN) cemented carbide tool in machining Inconel 718 [8]. Nalbant et al. have reported that the cutting speeds have much more influences on the surface roughness than different cemented carbide inserts in machining Inconel 718 using coated tools [2]. Song et al. have proposed that coating peeling is the main feature of tool wear for coated carbide tools in machining Inconel 718 [9]. Fan et al. have studied the tool wear of uncoated and coated cemented carbide tools in machining Inconel 718. They found that the tool wear is caused mainly by the formation and dropping of built-up-edge or wear debris formed by tool material fell off from the tool body [10].

In this work, the wear morphology of tool was observed by CCD and scanning electron microscopy to analyze the wear mechanism in dry machining Inconel 718 with cemented carbide tool. Based on tool wear mechanism analysis, tool wear model have been established to predict tool flank wear.

2. Material and experimental procedure

The work piece used in this study is Inconel 718 with a diameter of 100 mm. The Chemical compositions and mechanical properties of Inconel 718 are as follow (Table 1 and Table 2).

| material | Chemical composition (Wt.%) |
|----------|----------------------------|
|          | Ni | Cr | Nb | Mo | Ti | C | Si | Mn | B | Fe |
| Inconel 718 | 51.75 | 17 | 5.15 | 2.93 | 1.07 | 0.042 | 0.21 | 0.03 | 0.006 | last |

| material | Density ρ (kg/m³) | Yield σ0.2 (MPa) | Tensile σb (MPa) | Elongation δb (%) | Shrinkage ψ (%) | Toughness ak (J/cm²) |
|----------|-------------------|------------------|-----------------|------------------|----------------|------------------|
| Inconel 718 | 8280 | 1260 | 1430 | 24 | 40 | 40 |

Dry turning of Inconel 708 with cemented carbide tool was conducted on the CA6140 lathe. The informations of tool are shown in Table 3. The wear morphologies of cemented carbide tool were measured by CCD observation system and SEM. The average cutting temperature was measured by natural thermocouple. The cutting force measurement system, composing of Kistler 9257B three-dynamometer, 5007 charge amplifier, and data acquisition card, was used to measure the cutting forces.

The cutting speed vc is an important affection factor on the tool life. The experiments have been carried out at different cutting speeds, while fixing the feed rate at 0.1mm/r and the cutting depth at 1mm.
Table 3 The informations of tool

| Tool type          | Coating material | Rake angle γ₀ | Flank angle α | Cutting edge angle κγ |
|--------------------|------------------|---------------|---------------|----------------------|
| SNMG120408-AC520U  | PVD-TiAlN        | 9             | 7             | 45                   |

3. Results and discussion

3.1 Tool adhesive breakage

At the cutting speed \( (v_c) \) of 15 m/min and 25 m/min, the main form of tool wear was adhesive breakage of tool nose, which was shown in Fig.1.

At the cutting speed of 40 m/min, the patterns of tool wear changed. As shown in Fig.2, there was a little adhesion material and micro-chipping on the rake face. The Ni and Fe elements were found on the rake face of the cemented carbide tool. Due to the high cutting temperature in the process of machining, Ni and Fe elements diffused from the Inconel 718 alloy to the cemented carbide tool. The O element was also found on the rake face. These results indicated that there are two forms of wear, diffusion wear and oxidation wear, on the tool-chip interface under the high cutting speed.

Under the action of high temperature and pressure in the cutting zone, the adhesion points on the surface of cemented carbide tools and Inconel 718 materials moved comparatively. The metal particles were subjected to cut or stetched, and then were taken away by the other side, forming the adhesive wear. The chip and workpiece material moved along the rake face and flank face respectively. The oxidation layer and adsorbed film on the tool surface of workpiece were broken, making the material of the workpiece adhered to the surface of the cutting tool. The built-up-edge and unstable adhesive material were formed. As the cutting process went on, the unstable adhesive material fell off, and the tool adhesive breakage occurred.

Fig.2 Wear morphology and EDS analysis \((v_c=40\text{ m/min})\)
3.2 Tool friction wear
In the process of machining Inconel 718, there were sliding frictions between the tool and the workpiece, which made the tool material fell off from the tool matrix in a lamellar form, resulting in tool wear on the rake face and the flank face. (Fig.3).

In the process of machining, the tool surface underwent huge stress impact, which was formed by the normal load and tangential load on the tool surface. The holes and dislocations accumulated on the subsurface layer, then joined together and expanded to the surface. The thin layer of wear debris was finally generated and separated from the tool substrate, as shown in Fig.4.

The Fe and Ni in material and Co in the cemented carbide tool are the same group elements, which have great affinity. The elements diffused each other because of the high temperature and pressure in the contact zone. The Fe and Ni in the workpiece diffused into the bonded phase of cemented carbide tool, so the bond strengths between carbide particles (WC, TiC, TaC) and binder (Co) was reduced. At the same time, the Fe and Ni were oxidized and formed oxidation, such as Fe₂O₃ and Co₂O₄. The diffusion and oxidation process reduced the strength of the tool. With the increase of oxide, wear debris peeled off from the tool surface, resulting in more tool wear. The higher the cutting speed goes, the more severe the wear gets.

3.3 Modeling tool wear
In machining of Inconel 718 by the cemented carbide tool, the main reason of tool wear was that the wear debris peeled off from the tool substrate in a lamellar form, accompanied by oxidation and diffusion, These wear modes are classified as sliding wear. Therefore, the tool wear model is established by means of sliding wear delamination theory. According to literature [11], the model can be expressed in the following way:

\[ h = C \frac{P \cdot dl}{\sigma_f} \]

Where, \( C = \frac{Gb}{4\pi(1-\nu)} \). It is a constant.
In the process of cutting, the normal load of the tool surface varies with the change of feed speed, cutting speed and flank wear width $h_0$. The normal load can be expressed as:

$$p = k_1 v_c^a h_0^b h_0^c$$

(2)

According to the geometry of tool wear (Fig.5), when wear debris is formed, the increment of the flank wear width is:

$$dh_0 = h \cdot (1 - \tan \alpha \tan \gamma_0) \cdot \frac{1}{\tan \alpha}$$

(3)

That is:

$$dh_0 = h \cdot (ctg \alpha - \tan \gamma_0) \cdot \frac{1}{2 \cdot 1}$$

As:

$$h = c \frac{p \cdot dt}{\sigma_f}, \quad dl = v_c dt, \quad p = k_1 v_c^a h_0^b h_0^c$$

(4)

$$dh_0 = c \frac{k_1 v_c^a h_0^b h_0^c \cdot dt}{\sigma_f} (ctg \alpha - \tan \gamma_0)$$

(5)

The tool geometry parameters were set as constant $K$. The eq. (5) was rewritten as:

$$dh_0 = CK \frac{k_1 v_c^a h_0^b h_0^c \cdot dt}{\sigma_f}$$

(6)

Integrating both sides, this equation can be rewritten as:

$$h_0 = [CK(1-c)]^{\frac{1}{c}} \left( \frac{k_1 v_c^a f^b \cdot t}{\sigma_f} \right)^{\frac{1}{c}} + A$$

(7)

When $t=0$, $h_0=0$, we can get $A=0$. Letting $[CK(1-c)]^{\frac{1}{c}} = C_0$(constant), equation (7) could be rewritten as:

$$h_0 = C_0 \left( \frac{k_1 v_c^a f^b \cdot t}{\sigma_f} \right)^{\frac{1}{c}}$$

(8)

In order to obtain the wear model of machining Inconel 718, the Taguchi method was used to carry out experiments involving tool AC520U. The influence factors were cutting speed, feed rate and cutting time. The corresponding temperature, flank wear $h_0$ and feed force were measured, as shown in Table 4.

| Table 4 Orthogonal table of cutting experiments |
|-----------------|---------------|--------|-------|---------|------|
| $v_c$ (m/min)   | $f$ (mm/rev)  | $t$ (min) | $T$ (°C) | $h_0$ (mm) | $P$ (N) |
| 20              | 0.08          | 0.5    | 510    | 0.05     | 258   |
| 20              | 0.1           | 2      | 520    | 0.11     | 271   |
| 20              | 0.12          | 4      | 534    | 0.15     | 292   |
| 20              | 0.16          | 6      | 550    | 0.18     | 305   |
| 30              | 0.08          | 4      | 590    | 0.08     | 252   |
| 30              | 0.1           | 6      | 615    | 0.14     | 274   |
| 30              | 0.12          | 0.5    | 595    | 0.04     | 281   |
According to the experiment data, the empirical formula can be expressed as:

\[ P = 576.8828 v_c^{-0.0417} f^{0.258} h_0^{0.0146} \]  

(9)

According to literature [12], the relation between fraction intension and temperature of WC-Co carbide can be written as:

\[ \sigma_f = f(\theta) = 371 + \frac{1766}{1 + e^{0.768}} \]  

(10)

As:

\[ \theta = 209.5579 v_c^{0.3599} f^{0.0714} \]  

(11)

Substituting the expression for \( \theta \) in Eq. (7) from Eq. (11) yields:

\[ h_0 = C_0 \left[ \frac{576.8828 v_c^{0.0981} f^{0.288} t}{371 + \frac{1766}{209.5579 v_c^{0.3599} f^{0.0714}} - \frac{1}{1 + e^{0.768}}} \right] \]  

(12)

Substituting the values of \( h_0 \) and \( t \) obtained from experiments in Eq. (12) yields:

\[ C_0 = 0.0099 \]  

(13)

Substituting the expression for \( C_0 \) in Eq. (12) from Eq. (13) yields:

\[ h_0 = 0.0099 \left[ \frac{576.8828 v_c^{0.0981} f^{0.288} t}{371 + \frac{1766}{209.5579 v_c^{0.3599} f^{0.0714}} - \frac{1}{1 + e^{0.768}}} \right] \]  

(14)

The values of flank wear \( h_0 \) calculated through Eq. (14) and measured in experiments are shown in Fig.6. Excellent experimental agreement was achieved in wear prediction of cemented carbide tool machining Inconel718.

![Fig.6 Comparisons of experimental and predicted results of tool flank wear \( h_0 \)](image)

Fig. 6 Comparisons of experimental and predicted results of tool flank wear \( h_0 \)

4. Conclusions
This study analyzed the tool wear modes and mechanisms of cemented carbide tool in dry machining Inconel718. The main conclusions are as following:
(1) At low cutting speed, the cutting tool breakage occurred, which was caused by the formation and shedding of built-up-edge.

(2) A new wear mechanism was proposed. In the cutting process, the wear debris formed and peeled off from the tool substrate leading to tool wear. With the increase of cutting speed, the diffusion and oxidation between the tool and the workpiece weakened the tool strength. The sliding friction between the tool and the workpiece caused the wear debris to form and to peel off easily, thus accelerating the tool wear.

(3) According to wear mechanism, the tool wear model is established by means of sliding wear delamination theory. Excellent experimental agreement was achieved in the prediction of wear of cemented carbide tool in machining Inconel718.

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Nomenclature

\( v_c \): Cutting speed
\( f \): Feed rate
\( a_p \): Cutting depth
\( h \): Thickness of wear debris
\( h_0 \): Flank wear width
\( \sigma_f \): Fraction intension of the tool
\( dl \): Cutting length
\( G \): shear modulus (the ratio of shearing stress and shearing strain)
\( B \): Brugers vector
\( \nu \): Poisson's ratio
\( P \): Normal load
\( h_D \): Cutting layer thickness
\( t \): Cutting time
\( \gamma_0 \): Rake angle of the cutting tool
\( \alpha \): Relief angle of the cutting tool
\( \kappa_e \): Cutting edge angle
\( \theta \): Cutting temperature

\( K, k_1, a, b, c, C, C_0 \) are empirical constants

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