Tool wear mechanism of turning Inconel 718 and EEMD-based feature analysis

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Abstract: In the cutting process of high-temperature alloys, the performance of the tool is closely related to the surface quality of the workpiece. In this paper, a turning test was conducted on nickel-based high-temperature alloy Inconel 718 using PVD-coated carbide tools, and the microscopic morphology of tool wear was observed by scanning electron microscopy (SEM), and the chemical elemental composition of the tool wear surface was analyzed by energy spectrum analyzer (EDS), and the wear mechanism of PVD-coated carbide tools in three stages of tool wear was analyzed in detail. On this basis, the characteristic quantities closely related to tool wear were extracted in the time and frequency domains by the collected cutting force signals, which provide effective characteristic inputs for the subsequent study of online tool wear monitoring.

1. Introduction

Nickel-based high-temperature alloy Inconel 718 is characterized by high strength, high plasticity and work hardening. And as a typical difficult-to-machine material [1], there is a problem of severe tool wear during its cutting process, which leads to poor surface quality of the workpiece [2]. In the cutting process of high-temperature alloys, the superiority of tool machining performance is closely related to the good or bad surface quality of the workpiece. Therefore, it is necessary to study the wear mechanism of tools and monitor the wear process of tools to use them rationally and prolong their life.

In turning of nickel-based high temperature alloys, Thakur et al [3] showed that cutting speed has a significant effect on the rear face wear of the tool and the rear face wear rate is very uniform when the cutting speed is in the range of 45-55 m/min. Furthermore, Akhtar W et al [4] found that bonded wear was the dominant wear mechanism when turning Inconel 718 using coated carbide tools and was present at almost all cutting speeds. Hao et al [5] studied the rear tool face wear process of turning nickel based high temperature alloys and found that shedding of tool material from the tool substrate in the form of abrasive chips was the main cause of tool wear. Both elemental diffusion and oxidation reactions between the tool and the workpiece accelerate the formation and flaking of wear chips.

Tool wear monitoring can be divided into direct and indirect methods [6]. The indirect method is based on the principle of extracting feature quantities closely related to tool wear and then inputting...
them into a feature recognition model to characterize the state of wear through the recognition model [7]. When monitoring tool wear, the signal measured by the sensor contains a large amount of interference information such as noise in addition to information related to tool wear, so it is necessary to extract the feature values of the signal reflecting the tool wear state and then carry out subsequent analysis. Empirical modal decomposition (EEMD) is an algorithm for decomposing signals, which uses white noise to provide uniformly distributed scales in the time-frequency space [8]. In 1988, Norden E Huang et al. proposed a new adaptive time-frequency signal analysis method, namely empirical modal decomposition (EMD), which has strong adaptability and high[9]. Chi et al [10] used the ensemble empirical modal decomposition (EEMD) method to avoid the modal overlap in the signal decomposition process and to decompose the vibration signal in the milling process to extract the features closely related to the tool wear state.

In this paper, the wear mechanism of PVD-coated cemented carbide tools in three stages of tool wear was analyzed in detail based on the microscopic morphology and chemical elemental composition of tool wear area through Inconel 718 turning test. Then, the cutting force signals during machining of the high temperature alloy are decomposed in the time-frequency domain based on the EEMD theory, and the approximate entropy, sample entropy, and fuzzy entropy are extracted from the decomposed IMF components as the feature quantities for tool wear state identification, which provide inputs for the subsequent tool wear online monitoring and identification model.

2. Experimental design

2.1. Test platform construction

In this study, the cutting test was completed on a CAK3665 lathe, and the insert used was SCMT09T304FP, PVD coated carbide tool (Kennametal brand KCU10) with 7° back angle and 0.4mm tip radius, whose the coating is AlTiN. The workpiece is φ110mm × 300mm nickel-based high temperature alloy (Inconel718) bar, and the YDC-Ⅲ89B piezoelectric force measuring sensor was used to measure the three-way cutting force of the whole cutting process, and its sampling frequency is set to 4000Hz.

2.2. Test conditions and scheme

The test was conducted by external turning method with cutting parameters as shown in Table 1. During the test, when each cutting path of the tool reached 10m, the tool was removed and used KeyenceVHX-2000 super depth-of-field microscope to observe the wear morphology of the rear tool face and measure the wear value of the rear tool face.

Table 1. Inconel 718 cylindrical turning parameters

| No.  | Speed(m/min) | Feed(mm) | Depth of cut (mm) |
|------|--------------|----------|------------------|
| tool1| 30           |          |                  |
| tool2| 50           | 0.15     | 0.1              |
| tool3| 70           |          |                  |

3. Experimental results and analysis

3.1. Analysis of tool wear mechanism

As shown in Figure 1, the tool wear curve can be divided into three stages: initial wear, normal wear and sharp wear according to the trend of $VB$ with turning distance $L$. In the initial wear stage, due to the sharp cutting edge, the contact area between the tool and the workpiece is small, and the tool wear increases faster, and the contact area between the tool and the workpiece becomes larger in the normal wear stage, and then the tool wear enters a stable stage. In the rapid wear stage, the tool wear increases rapidly. Among them, the normal wear of the tool occupies the most of the entire wear stage, and the increase of cutting speed shortens the normal wear stage, which leads to the early sharp wear stage of the tool and thus affects the entire wear process of the tool.
Figure 1. Tool rear face wear curve

Figure 2 shows the rear tool face wear images of the initial wear stage, normal wear stage and sharp wear stage of tool2 at a magnification of 200x using a super depth-of-field microscope, and the wear mechanisms of the three stages of tool wear were analyzed by scanning electron microscope photographs.

Figure 2. tool2 rear tool face wear image. a. Initial wear VB=0.185mm b. Normal wear VB=0.242mm c. Sharp wear VB=0.292mm

In the initial wear stage of the tool, shown in Figure 3, the wear mechanism was found to be mainly bonded wear, and EDS analysis of the bonded material in area 1 by energy spectrometer revealed that the bonded material in this area contained Ni, Cr and Fe elements, which proved that it was the workpiece material nickel-based high-temperature alloy bonded on top of the tool. And the coating material elements Ti, Al and N were few, indicating that the tool’s coating had started to flake off.

Figure 3. Microscopic morphology and EDS analysis at the initial wear stage. a. Tool rear tool face wear image (500x). b.1 Area EDS analysis

In the normal wear stage of the tool, shown in Figure 4, the area of the rear tool face wear increased significantly compared to the initial wear stage, and the main form of wear was still dominated by bonded wear. EDS analysis of the bonded material in area 1 revealed that the change in the material in this wear area was not significant, and it was still the workpiece material adhering to the tool surface. In addition, EDS analysis of area 2 shows that a large amount of W elements can be seen, which indicates that the coating on the tool surface in contact with the machined surface has peeled off, exposing the tool substrate.
Figure 4. Microscopic morphology and EDS analysis of normal wear stage. a,b. Tool rear tool face wear image (500x) (3000x). c.d. 1,2 area EDS analysis

In the sharp wear stage of the tool, shown in Figure 5, it was found that the bond layer produced in the normal wear stage broke and took away part of the tool material, and an obvious chipping phenomenon occurred at the edge of the tool as shown in Figure 5, which led to the increase of tool wear. After EDS analysis of the area, it was found that in addition to the tool base material elements, O, workpiece material elements Ni, Fe and Cr were also present in the wear area, indicating that oxidation wear and diffusion wear occurred in the tool during the rapid wear stage.

Figure 5. Microscopic morphology and EDS analysis of the sharp wear stage. a. Tool rear face wear image (500x). b. 1 area EDS analysis

3.2. Cutting force analysis

As the cutting path increases, the increase in tool wear leads to significant changes in cutting forces, cutting vibration, and cutting heat. In order to reduce the complexity of the acquisition signal system, only the cutting force signal is acquired and analyzed in this experiment. As shown in the figure 6, the radial force $F_y$ has the largest change in magnitude, increasing from 93 N to 222 N, probably due to the large modulus of elasticity (210 GPa) of Inconel 718. The axial force $F_x$ and the tangential force $F_z$ also increase as the tool wears. Among them, the tangential force $F_z$ increases more in the initial wear stage and the sharp wear stage, while the increase in the normal wear stage is more stable and has the strongest correlation with the tool wear curve.
Figure 6. Three-way cutting force of cutting process

4. Decomposition of cutting force signal based on EEMD

4.1. EEMD decomposition process
Since the tangential force $F_z$ has the strongest correlation with the tool wear curve, in this paper we use the tangential force $F_z$ to characterize the tool wear, and carries out the feature extraction of information entropy after the EEMD decomposition of the tangential force $F_z$ in the time and frequency domains. Two parameters, $Nstd$ and $NE$, are required in the EEMD decomposition process. $Nstd$ indicates the amplitude of the added white noise, and $NE$ indicates the number of EEMD decompositions. Figure 7 is Initial, normal and sharp wear stages IMF components and corresponding spectrum. As shown in the figure 7, after the tangential force $F_z$ signal is decomposed by EEMD, the spectral information corresponding to each group of IMF components gradually decreases with the increase of decomposition times. Therefore, the first six IMFs components are selected for feature extraction of information entropy in this paper.

Figure 7. Initial, normal and sharp wear stages IMF components and corresponding spectrum

4.2. Cutting force signal information entropy extraction
When the tool wears, it affects the complexity of the cutting force signal, so the information entropy of the cutting force signal can be extracted as a characteristic quantity to express the tool wear state intuitively. Figure 8 is Information entropy of initial, normal and acute wear stages. As shown in the
Figure 8, after EEMD decomposition, the complexity of the signal decreases, and the information entropy such as fuzzy entropy, approximate entropy and sample entropy of the tangential force \( F_z \) decreases with the increase of the IMF component throughout the process of tool wear. Due to the increase of tool wear, the stability of the cutting system decreases, which leads to the increase of signal complexity, and all three entropy values increase with the increase of tool wear.

![Figure 8. Information entropy of initial, normal and acute wear stages](image)

5. Conclusion

The wear mechanism of PVD coated cemented carbide tools was investigated through the turning test of Inconel 718. Based on this, the feature quantities closely related to tool wear were extracted in the time-frequency domain from the collected cutting force signals to provide effective feature inputs for the tool wear online monitoring and identification model. 

The following conclusions can be drawn:

(1) The tool wear process can be divided into three stages according to the value of wear on the rear tool face: initial wear stage, normal wear stage and rapid wear stage. Using SEM and EDS analysis, it is found that there are different wear mechanisms of the tool in the three wear stages, i.e., bonded wear, oxidation wear and diffusion wear.

(2) The tangential force \( F_z \) is most strongly correlated with the tool wear process throughout the wear stage. After the EEMD decomposition of the tangential force \( F_z \) and the extraction of the feature quantity, it is found that its information entropy shows an increasing trend with the tool wear and the signal complexity increases.

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