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A power spectrum analysis of effect of rolling texture on cutting forces in single-point diamond turning

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Abstract

In most of the existing metal cutting theories, the workpiece is assumed to be homogeneous and most continuum theories do not take into account the effect of crystallographic anisotropy that causes variations in the shear plane at the grain level and hence of the cutting force. As the depth of cut in single-point diamond turning (SPDT) is usually less than the average grain size of a polycrystalline aggregate, cutting is generally performed within a grain. At this scale, the difference in the individual grain properties cannot be integrated out and a continuum solution would be insufficient. As a result, this paper presents a power spectrum analysis of the periodic fluctuation of micro-cutting forces in SPDT of polycrystalline materials. The experimental results show that the features of the power spectra of the cutting forces can be well correlated with the change of rolling texture of the materials being cut. These findings help to explain quantitatively the fluctuation of micro-cutting forces and hence the effect of rolling texture in SPDT, which are not encountered in conventional machining.

Keywords: Rolling texture; Power spectrum analysis; Single-diamond turning; Cutting forces; Polycrystalline

1. Introduction

Single-point diamond turning (SPDT) technology is a machining process making use of a mono-crystal diamond cutting tool, which possesses nanometric edge sharpness, forms reproducibility and wears resistance. In a polycrystalline material, each of the crystalline phases has an orientation that differs from those of its neighbors. It is unusual for the crystallites to have a random distribution of crystallographic orientations. The non-random distributions that occurred are called preferred orientations or crystallographic orientations.

The preferred orientation of grains is one important source of the plastic anisotropy, which may arise during the cold-working or annealing of a metal prior to the machining process. The cutting force and the shear angles have been found to vary with the orientations of the materials being cut.

In conventional cutting, the crystallographic orientation of the work materials has less significant effect since the polycrystalline materials are usually treated as an isotropy and homogenous material with respect to the depth of cut in macro range. However, the polycrystalline material must be treated as a series of single crystals with random orientations in SPDT as the depth of cut is usually less than the average grain size and the cutting is usually performed within a grain. In ultra-precision machining, crystallographic orientation as an important source of material anisotropy was found to exert a great influence on surface finish [1], cutting force [1,2], chip formation [3,4], and shear angle [5,6].

In this paper, a power spectrum analysis method is used to reveal the cutting force patterns. Hence, the quantitative relationships between the features of cutting force variation and the crystallographic orientation of work materials were explored. The results of analyses were compared with the cutting tests conducted on polycrystalline materials.

2. Theoretical background of power spectrum analysis of the cutting force variation

The cutting force variation was analyzed by power spectrum analysis. The power spectrum of the cutting force signal is determined by discrete Fourier transformation (DFT) computing with

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Table 1
Composition of the test materials

Material	Al 6061	Cu	CuNi
Aluminium	Remainder	99.95	–
Copper	0.15	–	68.3
Iron	0.7	–	0.55
Silicon	0.4–0.8	–	<0.1
Manganese	0.15	–	0.65
Magnesium	0.8–1.2	–	–
Chromium	0.04–0.35	–	–
Nickel	–	–	30.4
Zinc	0.25	–	0.03
Titanium	0.15	–	–
Others	0.15	Remainder	Remainder

a fast Fourier transformation (FFT) algorithm. The cutting force signal is denoted by $F(k)$ with $k = 0, 1, 2, \ldots, N-1$, where N is the number of samples in the force signal, and the power spectrum of the force signal is defined as:

$$Z(f_n) = \sum_{k=0}^{N-1} F(kl_s)\exp(-2\pi jkl_s f_n) \quad (1)$$

where n is an integer number, and f_n is a frequency component of the cutting force signal which represents the number of waves with a wavelength of λ_n within a unit period of time:

$$\lambda_n = \frac{1}{f_n} = \frac{T}{n}. \quad (2)$$

N is the total number of samples with spacing Δt taken within the measured time-period T of the force signal, i.e.:

$$N = \frac{T}{\Delta t}. \quad (3)$$

In order to prevent aliasing distortion [7], the sample rate f_{sample} must be chosen to be at least twice the highest non-zero frequency component $f_{\max}$ contained in the cutting force signal according to the sampling theorem or Nyquist criterion, i.e.:

$$f_{\text{sample}} \geq 2f_{\max} \quad (4)$$

Table 2
Cutting conditions

Experiment	A
Depth of cut (μm)	5
Cutting speed (rpm)	3000
Feed rate (mm/min)	20
Tool rake angle (°)	0
Tool nose radius (mm)	0.5
Front clearance angle	5

Δt should be:

$$\Delta t \leq \frac{1}{2f_{\max}} \quad (5)$$

In the present study, Δt is chosen to be 0.0002 s which ensures an accurate representation of the cutting force signal with frequency content up to 2500 Hz.

The power spectral density (PSD) is determined directly from the DFT. The periodgram $|Z(f_n)|^2$ is obtained by transforming the real data. This will yield N transformed points corresponding to N real data points. To minimise the distortion of the true spectrum due to Gibb's phenomenon, the spectral window corresponding to the Hanning lag window is applied to get the PSD [8]. The Hanning window is operated on the frequency data by means of convolution, i.e.:

$$\text{PSD}(f_0) = 0.25(Z(f_p))^2 + 0.50(Z(f_0))^2 + 0.25(Z(f_s))^2 \quad (6)$$

where PSD(f_0) is the power spectral density at a particular frequency f_0, f_p and f_s are the preceding and the succeeding frequencies for f_0, respectively.

3. Experimental procedures

In the present study, the polycrystalline aluminium alloy Al 6061, copper and copper nickel were used. The materials were straight and cross-rolled to obtain different crystallographic orientations. A series of face cutting tests were then performed on each of the specimens with a diameter of 12.7 mm diameter. The composition of the test materials are shown in Table 1. All cutting tests were performed on a two-axis CNC ultra-precision lathe (Optoform 30 from Taylor Hobson Pneumo Co., UK) under the same cutting conditions. The cutting conditions were tabulated in Table 2.

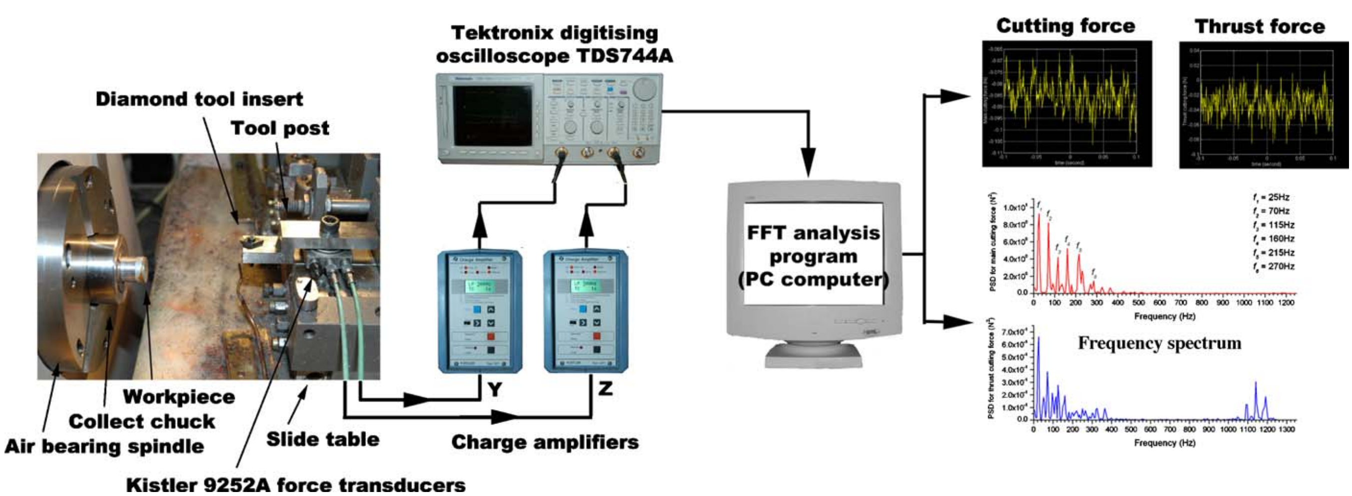

Fig. 1. Configuration of the experimental setup.