A novel approach to cutting force modelling in diamond turning and its correlation analysis on tool wear

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Abstract

In this paper, a novel cutting force modelling approach is proposed by employing the specific cutting force and quantitative analysis on the variation of dynamic cutting force so as to accurately represent the dynamic cutting force behaviour including both amplitude and spatial aspects simultaneously. The specific cutting forces at the unit cutting length and area can effectively represent the micro cutting phenomena particularly in relation with chip formation, surface generation, cutting temperature distribution and the corresponding tool wear, etc. The application of the cutting force modelling is further explored to the real-time detection of tool wear in diamond turning using correlation analysis based on wavelet transforms (WT). The cutting trials are carried out and supported with FEA-based simulations.

1. Introduction

Cutting forces in diamond turning or micro cutting processes are normally at 1N scale, and are currently modelled based on the absolute force values. The modeling techniques are limited in representing the micro cutting forces and the associated cutting physics, particularly in relation to the chip formation, surface generation and tool wear, etc.

This paper presents an innovative cutting force modelling technique using specific cutting force, e.g. the cutting forces at the unit length and area to represent its amplitude aspect, and the forces analyzed against the instant cutting variation time to represent its spatial aspect. The micro cutting mechanics and physics including chip formation and size-effects are analyzed and interpreted by the amplitude aspect, and the spatial aspect is carried out on tool wear correlation in diamond turning using WT in association with standard deviation analysis.

2. A proposed cutting force modelling approach

The micro cutting forces are usually at 1N scale and have different behaviors compared with those in conventional cutting. Consequently, the difficulties of scientific interpretations on the micro cutting mechanics, e.g. chip formation, size-effects, surface generation, tool wear by conventional cutting force modelling. Therefore, a novel cutting force modelling is essential and much needed particularly in instead using the absolute micro cutting forces and better interpreting the micro cutting mechanics in diamond turning processes. In this model approach, the specific cutting forces at the unit length and area are considered as the force amplitude aspect. The cutting force variance against a short-time cutting period is considered as the force spatial aspect. The proposed cutting force model can then be expressed as:

$$F_{Novel} = \begin{cases} \frac{F}{\Delta l}, \frac{F}{\Delta A} & \text{amplitude aspect} \\ \int_{\Delta t_0}^{\Delta t_1} F dt & \text{spatial aspect} \end{cases} \qquad (1)$$

3. Interpretation on size-effect phenomena by the force amplitude aspect

The FE-based simulation is used to validate the cutting force model and modelling techniques especially in interpreting the size-effect by considering the cutting force against the contact length which is equal to the chamfer length fabricated on the diamond cutting tool as illustrated in Fig.1. The cutting conditions in simulations are same as those used in experimental cutting trials. The chamfer length at the tool tip is varied with rake angles (α) and depicts the legends of cutting force and specific cutting force at every step of time interval - 5.0×10^{-6} second for total simulation time of 10^{-4} second. The simulation outcomes present significance analysis of micro cutting phenomena particularly in the size-effect interpretation.

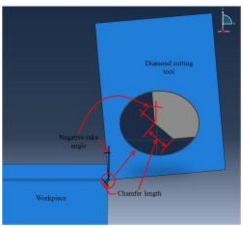

Figure 1: Illustration of the chamfer length and its variation against the rake angle in micro cutting aluminum AA6082-T6 (FEA-based simulation)

The legends of cutting forces in rake angle α = -50° and -70° are similar to each other through the FEA-based simulation by varying the chamfer length from 1 to 2 μm. The average cutting forces and specific cutting forces are as depicted in Fig. 2. It is found that the cutting force at α = -70° trends to decrease when the chamfer length is increasing, while the cutting force at α = -50° remains stable along all chamfer lengths (1-2µm). However, the specific cutting force at these two rake angles dramatically increases especially at α = -70° and reducing the chamfer length is applied. Furthermore, the pressure on the cutting edge is increased while the contact length is decreased especially at more negative rake angle, which indicates the corresponding correlation with the size-effect in the micro cutting.

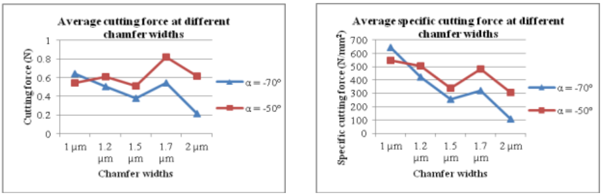

Figure 2: The average cutting force and specific cutting forces at different chamfer lengths with the rake angles at -50° and -70°

The investigations on size-effect have been undertaken by numerous studies [1] [2] with a particular focus on the tool edge radius being comparable to the undeformed chip thickness in ultraprecision and micro cutting. The specific cutting energy will increase nonlinearly as the undeformed chip thickness is decreased. The negative rake angle has significant effects on the size-effect in specific cutting energy. In this research, the specific cutting force modelling is proposed covering both the force amplitude and spatial aspects, which can represent the cutting mechanics and physics dynamically in the micro-effect context. For instance, if chamfer length is comparable to the undeformed chip thickness, the reducing chamfer length consequently leads to higher specific cutting force as theoretical aforementioned. The negative rake angle in this simulation outcome has also affected the size-effects, i.e. the larger the negative rake angle is applied, the higher the specific cutting force is dominated to the cutting process as illustrated in Fig.2. This illustrates the force amplitude aspect can interpret the size-effect in micro cutting better than using only absolute cutting force value. Furthermore, the comparison of experimental cutting and FE-based simulation validation has also been performed to show the simulations in good agreement with the cutting trials.

4 Analysis on the force spatial aspect in correlation with tool wear

The db03 of WT was selected to analyze the standard deviation of feed and cutting forces in cutting single crystal silicon. The standard deviation of raw signal (S) and the different wavelet coefficients include its low frequency component or approximation (A1), and high frequency component or details at level 1 (D1) to level 4 (D4) as extracted through Labview-based data processing. Fig. 3 shows the standard deviation of raw signal and its different wavelet coefficients at levels 1-4 of feed force and cutting force respectively.

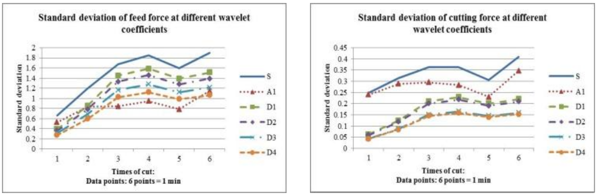

Figure 3: Standard deviation of raw signals of feed force (a: left) and cutting force (b: right), and theirs decomposition in different wavelet coefficients

As seen from Fig. 3, the shapes of D1 (a) and A1 (b) have the most similar trends to illustrate their raw signals (S) namely feed force (a) and cutting force (b) respectively. Thus, the D1 of feed force and A1 of cutting force are selected to further investigate how these components significantly affect the cutting process outcomes and the corresponding tool wear by decomposing approximation coefficient (A1) of feed force and the details coefficient of cutting force (D1) from the first cut to last cut (the sixth cut) on silicon wafer with a new diamond cutting tool. The result is clear that the amplitude of feed force D1 is dramatically increased until the third cut (from about 1.8N/µm to 7N/µm) caused by higher frequency bands at higher levels [3], and then slightly increased from the third to the last cut (about 7/µm to 9/µm). Meanwhile, the amplitude of cutting force A1 is slightly increased from the first to last cut, or even quite similar level at some cuts. Therefore, it can be assumed that the feed force is dominated to the cutting process outcomes and corresponding to tool wear rather than the cutting force. Consequently, that means tool wear can be occurred significantly caused by feed force since the first cut is taken. SEM photographs are also taken after the last cut to observe the tool wear for validation. The agreed results show that, the micro-fracture and the flank wear can be observed in the feed direction, while no crater wear is occurred in cutting force direction as illustrated in Fig. 4. In summary, the diamond tool wear is mainly caused by feed force in feed direction in cutting single-crystal silicon with the aforementioned cutting conditions as experimentally set up.

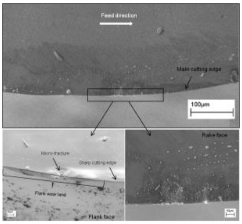

Figure 4: SEM photographs of the cutting edge being taken after the sixth cut

5 Conclusions

The novel cutting force modelling approach based on specific cutting forces is proposed instead using the absolute micro cutting force value, in order to better interpret the micro cutting mechanics and physics particularly the chip formation, size-effect, and corresponding tool wear in single point diamond turning process. This approach is presented as two particular aspects, i.e. the force amplitude aspect and spatial aspect respectively. The amplitude aspect is defined as cutting force at the unit area or unit length. Thus, the micro cutting phenomena especially on chip formation and size-effect are possibly better interpreted by the force amplitude aspect. The spatial aspect is analyzed as the cutting force variance at a short cutting time. The application study of spatial aspect is carried out on its correlation analysis with the tool wear detection by using WT techniques correlated to standard deviation analysis. The analysis on standard deviation of feed fore and cutting force signals decomposition is capable for detecting tool wear in real time machining, likely supported by using a smart cutting tool embedded with such cutting force algorithms [4]. This technique can also lead to classifying the types of tool wear simultaneously.

References:

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