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An innovative investigation on chip formation mechanisms in micro-milling using natural diamond and tungsten carbide tools

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ABSTRACT

This paper presents an analytical approach to investigating the chip formation process in micro-milling aluminum 6082-T6 particularly by using natural diamond and tungsten carbide tools. Through well-designed micro-milling experiments, a comparative study is conducted by utilizing a natural diamond tool with the perfectly sharpened cutting edge and a tungsten carbide tool with the rounded cutting edge respectively. Cutting forces are recorded and analyzed as one of main process indicators. The chip morphology and micro milling processes are analyzed in correlation with cutting force variations in the processes. The size effect, minimum chip thickness and their integral effect are quantitatively assessed against the chip formation process. Research results show that the chips formed during the consecutive revolutions are affected jointly by the cutting tool/workpiece material pair and the cutting edge radius in using tungsten carbide tools; whereas the chips formed by using diamond tools are intact and separate. Furthermore, the cutting force and thrust force are of the same order due to the cutting edge radius cannot be ignored. For using a natural diamond tool with the sharp cutting edge, the resultant cutting force is usually two times higher than the thrust force.

1. Introduction

Since late 1990s, there has been an increasing demand for compact, integrated and miniature products for use in our daily life as well as for industrial applications. Many miniature and micro components or products are made from aluminum alloys because of their engineering material properties and wide applications particularly in aviation and aerospace industries [1]. The chip formation process in micro milling homogeneous aluminum material is quite different from that in the conventional milling process. The most prominent phenomenon is the size effect, which is understood as the increases of the specific cutting force with decreases in cutting thickness. Due to the existence of the non-negligible cutting edge radius, the cutting tool may keep ploughing the workpiece surface and consequently there is no chip formation in micro milling with a very small depth of cut. In this scenario, the workpiece material undergoes pure elastic deformation when the cutting tool goes through and then the workpiece material recovers to the original height or less. With the continuous increase of the cutting depth, the material plastically deforms partially and the chips start to form only if the uncut chip thickness approaches a certain threshold. Therefore, the chips can be formed and removed only when the depth of cut exceeds the minimum chip thickness. This is normally known as the minimum chip thickness effect [2–7]. This effect distinguishes the micro milling substantially from the macro milling. The quantitative identification of the minimum chip thickness is a critical issue in micro milling, which has been investigated by many researchers [8,9]. It is widely accepted that the chip formation in micro cutting is separated into two regimes: ploughing dominant regime and shearing dominant regime. The scientific and systematic understanding of the chip formation process in micro cutting, especially in micro milling, is essential and much needed particularly against the increasingly stringent requirement for industrial scale micro milling operations.

The research presented in this paper attempts to investigate an industrial feasible analytical approach for scientific understanding the chip formation process in micro milling and the associated technological perspectives in machining applications. The innovative investigation on chip formation mechanisms by using natural diamond and tungsten carbide micro milling tools is carried out through theoretical exploration, modelling and analysis of the micro cutting mechanics particularly the micro milling forces modelling and analysis. The chip formation and micro cutting forces are

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Nomenclature

$F_x(t)$, $F_y(t)$ Orthogonal cutting force and thrust force (N)
$F_{Sx}(t,k)$, $F_{Sy}(t,k)$ Specific cutting force and specific thrust force (N)
R Nominal radius of cutting tool (μm)
β Helix angle of cutting tools (°)
θ_{en} Engage entry angle of cutting flute (°)
θ_{ex} Disengage exit angle of cutting flute (°)
A_p Ploughing area between the tool and workpiece (μm^2)
θ Position angle of kth tooth (°)
K_{rp},K_{tp} Ploughing coefficients in radial and tangential directions (N/mm^2)
K_{re},K_{te} Edge constants in radial and tangential directions (N/mm^2)
K_{rc},K_{tc} Cutting force coefficients in radial and tangential directions (N/mm^2)
$h(\theta i(z))$ Uncut chip thickness (μm)
z Axial height of flute (μm)
t Time point of milling process (s)
k Tooth number of micro mill /

further evaluated and validated with well-designed experimental trials.

2. Analysis and insight into chip formation mechanism in micro milling

In micro milling aluminum 6082-T6 by using nature diamond tool and tungsten carbide tool, cutting process behaviors and cutting performances including the cutting mechanics, chip formation, surface generation and tool wear can be analyzed from the cutting force even for a complex cutting process with various process variables [10]. Due to the cutting force can be achieved from modelling technique and experiments, the cutting mechanics particularly for the chip formation mechanics can be accurately analyzed afterwards. According to the measured cutting force and thrust force data in micro milling process, the chip formation mechanisms such as the minimum chip thickness and chip breakage can be easily predicted in conventional cutting process. However, previous research and experiments show that cutting forces in micromachining are quite small down to the 0.1–1N scale in magnitude. The direct usage of absolute cutting force imposes the technical challenge in accurate measurement of the micro cutting forces particularly in the cutting process. Thus, the chip formation mechanisms cannot be predicted accurately based on the absolute cutting force values. Furthermore, it is essential in developing the cutting force modelling for bridging the gaps between understanding the micro cutting mechanics and the process optimization and cutting performance enhancement. Therefore, an innovative cutting force modelling is proposed to provide insightful quantitative analysis into micro milling mechanics and the process, which is further presented in details below.

Since the micro milling force is at 0.1–1N scale, the cutting force at the unit area is presented as the specific cutting force so as to better illustrate the underlying chip formation mechanisms in relation to micro cutting forces. The specific cutting force that acts at the contact area through the tool tip and workpiece interaction is considered as the effective force, which leads to the chip formation and the resultant surface generation. In addition, the specific cutting force at the unit area can be closely linked with the material Young's modulus, i.e. the ultimate strength of the workpiece material, which can provide micro mechanics insights on the chip formation and breakage, surface generation and even the tool wear at both rake and flank surfaces of a milling tool. The specific cutting force at a unit area overcoming the ultimate strength in the chip formation is expressed in Eq. (1):

$$F_{Sx}(t,k) = \frac{F_x(t)}{S} \qquad F_{Sy}(t,k) = \frac{F_y(t)}{S} \tag{1}$$

Where, $F_x(t)$, $F_y(t)$ are the orthogonal cutting forces in chip formation process. The integrated cutting forces over the range of engagement of each cutting flute against the workpiece material are illustrated in Eqs. (2) and (3):

When the cutting chip thickness is smaller than minimum chip thickness,

$$\begin{aligned} F_x(t) &= R\cot\beta \int_{\theta_{en}}^{\theta_{ex}} (K_{rp}A_p\sin\theta + K_{re}\sin\theta + K_{tp}A_p\cos\theta + K_{te}\cos\theta)d\theta \\ F_y(t) &= R\cot\beta \int_{\theta_{en}}^{\theta_{ex}} (K_{rp}A_p\cos\theta + K_{re}\cos\theta - K_{tp}A_p\sin\theta - K_{te}\sin\theta)d\theta \end{aligned} \tag{2}$$

When the cutting chip thickness is larger than minimum chip thickness,

$$\begin{aligned} F_x(t) &= R\cot\beta \int_{\theta_{en}}^{\theta_{ex}} (K_{rc}h(\theta_i(z))\sin\theta + K_{re}\sin\theta + \ldots + K_{tc}h(\theta_i(z))\cos\theta + K_{te}\cos\theta)d\theta \\ F_y(t) &= R\cot\beta \int_{\theta_{en}}^{\theta_{ex}} (K_{rc}h(\theta_i(z))\cos\theta + K_{re}\cos\theta - \ldots - K_{tc}h(\theta_i(z))\sin\theta - K_{te}\sin\theta)d\theta \end{aligned} \tag{3}$$

Where, R is nominal radius of cutting tool; β is the helix angle of cutting tools; θ_{en} and θ_{ex} are the entry angle and exit angle of cutting flute when it engages and disengages with workpiece material; A_p is the ploughing area between the tool and workpiece; θ is the position angle. K_{rp}, K_{tp} are the ploughing coefficients in radial and tangential directions respectively; K_{re}, K_{te} are the edge constants in radial and tangential directions respectively; K_{rc}, K_{tc} are the cutting force coefficients contributed by the shearing action in radial and tangential directions respectively.

Due to the periodical changes of cutting chip thickness, both ploughing dominant cutting and shearing dominant cutting will take place in each revolution. Thus, the cutting forces should be calculated comprehensively by combining Eqs. (2) and (3).

For ultra-precision micro milling, the cross section of the chip generated in micro milling is also a function of position angle. The cross section can be formulated in Eq. (4):

$$S = \frac{R}{\sin\beta}\int_{\theta_{en}}^{\theta_{ex}} h(\theta_i(z))d\theta \tag{4}$$

Where, $h(\theta i(z))$ is the uncut chip thickness which is a function of tool position angle θ and flute axial height z; t is the time point of milling process; k is the tooth number of micro mill. Thus, the specific cutting force at unit area that overcomes the ultimate strength for the chip formation shown in Fig. 1 can be formulated as Eq. (5):

$$F_{Sx}(t,k) = \frac{F_x(t)\sin\beta}{R\int_{\theta_{en}}^{\theta_{ex}} h(\theta_i(z))d\theta} \qquad F_{Sy}(t,k) = \frac{F_y(t)\sin\beta}{R\int_{\theta_{en}}^{\theta_{ex}} h(\theta_i(z))d\theta} \tag{5}$$

Thus, the cutting force at the unit area that presented as the specific cutting force clearly illustrates the insightful mechanics on the chip formation and breakage. This specific cutting force also bridge