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Study on performance in dry milling aeronautical titanium alloy thin-wall components with two types of tools

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ABSTRACT

Cutting fluid may be considered an accessory which is frequently applied in order to increase material remove rate especially in cutting aerospace alloys where cutting temperature is very high. However the use of cutting fluids is nowadays limited due to the adverse effects such as health of the operator, environmental and economic reasons. In order to overcome these negative effects and meet the demand for environment-friendly cutting techniques, in this work, dry cutting is associated to compare the machinability of the two types of tools such as variable and uniform pitch tools in milling aeronautical thin-wall material Ti6Al4V. The experimental results have shown that the tool vibration is decreased obviously with variable pitch tool compared with uniform pitch tool during milling process of titanium alloy thin-part components. The vibration minimizing characteristics of variable pitch tool is analyzed using fast Fourier transform and wavelet analysis in the whole milling process.

1. Introduction

Titanium alloys have been used extensively in the aerospace industry due to their excellent performance in the aerospace environment such as high strength-to-weight ratio, lower density, and superior resistance to oxidation, corrosion, fatigue and fracture (Ezugwu and Wang, 1997). However, titanium alloys are one of well known difficult-to-machine materials owing to the following characteristics: 1) their poor thermal conductivity causes inefficient dissipation of machining heat resulting in very high temperatures near the cutting edge (Machai et al., 2013); 2) low elastic modulus and high chemical activation can result in tool vibration and wear, ultimately shorten tool life and affect surface finish (Huang et al., 2012). Machining of these alloys is characterized by low cutting speeds and depths of cut, which implies a low material removal rate (MRR). At the same time, the large volume of materials need to be removed from roughcast due to the structural design characteristics in the aerospace industry, where thin-walled structures are widely used due to their higher structural efficiency and light weight characteristics. This is generally not desirable in industrial machining since it increases the cutting time and cost. These are some constraints in the development of aerospace titanium alloy. So it is very necessary to increase productivity in cutting aeronautical difficult-to-machine material.

Conventionally, cutting fluid is widely used in order to reduce the cutting temperature especially in machining difficult-to-machine material. But the use of cutting fluids is being questioned due to the health and environmental impacts (Shashidhara and Jayaram, 2010). Moreover, for the companies, the costs related to cutting fluids represent a large amount of the total machining costs which has been estimated that the cost of cutting fluids is approximately 7–17% of the total cost in machining process (Lawal et al., 2013). So there are critical needs to reduce the usage of cutting fluid in machining process in order to meet the demands for environment-friendly cutting processes. Recently, Marksberry (2007) used a micro-flood (MF) technology for minimizing the use of cutting fluid during turning SAE 070Y steel, and the experiment results show MF technology can be recognized as a coolant-less and occupational health friendly technology capable of providing improved machining performance without creating undesirable spray mist entropy. Nandy et al. (2009) applied high-pressure coolant jets to direct into the tool–chip interface to enhance tool life and increase productivity in turning Ti–6Al–4V, and the result shows that tool life on high-pressure cooling with water-soluble oil improved at least by 250% over that in conventional wet environment. Sanchez et al. (2010) investigated a new

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approach based on the use of a hybrid minimum quantity of lubrication (MQL) low temperature CO_2 systems to the elimination of cutting fluids in surface grinding AISI D2 tool steel experiments, which resulted in a significant improvement in grinding wheel life and surface quality of the machined component. Fratila and Caizar (2011) used dry cutting and minimal quantity lubrication techniques during face milling of AlMg3 process to meet cleaner manufacturing, and the study confirms that the near-dry techniques can be successfully applied without affecting the machining process results. Zhang Wang (2012) investigated tool life and cutting forces in end milling Inconel 718 under dry and minimum quantity cooling lubrication cutting conditions (MQCL), and the study shows that MQCL cutting with biodegradable vegetable oil meet the increasing demands for cleaner manufacturing of Inconel 718.

However, the high cost of delivery system and equipment of cutting fluid has limited its popularization and application in machining industry. Another effective method to improve productivity in cutting titanium alloy is to use proper tool materials. A major requirement of tool materials used for machining these alloys is that they must possess resistance to elevated temperatures. Advances in cutting tool materials and machining techniques have resulted to significant increase in metal removal rate when cutting difficult-to-cut aerospace superalloys (Ezugwu, 2005). However machining productivity can be significantly improved by employing the right combination of tools structure and cutting parameters on the basis of using suitable tool materials. The use of a non-standard cutting tool, i.e. variable pitch tools has been proposed to decrease cutting vibration by disrupting the regenerative effect (Quintanaa and Ciurana, 2011), correspondingly decrease cutting temperature and tool wear.

The pitch of tool p is the distance from a point on the cutting edge to another point in next cutting edge seen from Fig. 1. Variable pitch tools includes two types: variable helix angle (seen from Fig. 1(a)) and variable pitch angle (seen from Fig. 1(b)). Assuming the tools have 4 cutting edges, and then the following conditions are satisfied for variable pitch tools: β_i are not all equal; ϕ_{pi} are not all equal, where, β_i is the helix angle of cutting edge i, and ϕ_{pi} is the pitch angle between cutting edge i and cutting edge $i+1$.

Variable pitch tools were initially proposed by Slavicek (1965) for chatter suppression. It can disturb the regenerative chatter by phase shifts from one flute to next at each revolution and prevent the build up of chatter vibration energy during machining (Merdol and Altintas, 2004) because of their unequal pitch distribution. The vibration reduction mechanism of variable pitch end mills was analyzed by the theory of energy balance of frequency spectrum line of cutting force by Huang et al. (2013), which is the spectrum lines' energy distribution is more intense to use variable pitch tool than to use uniform pitch tool, so the forced vibration is reduced.

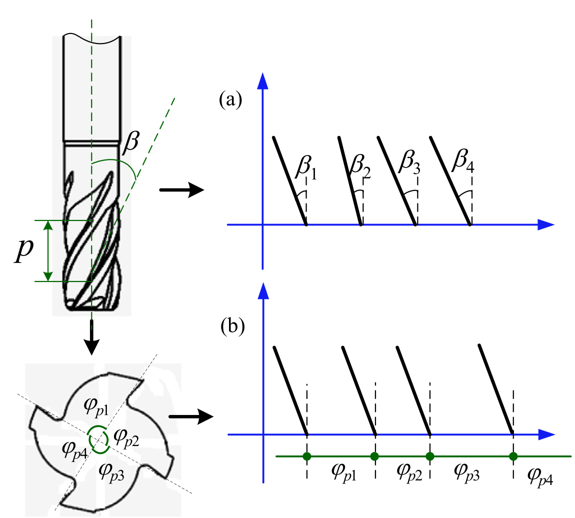

Fig. 1. Variable Pitch tool: (a) variable helix angle end tool and (b) variable pitch angle end tool.

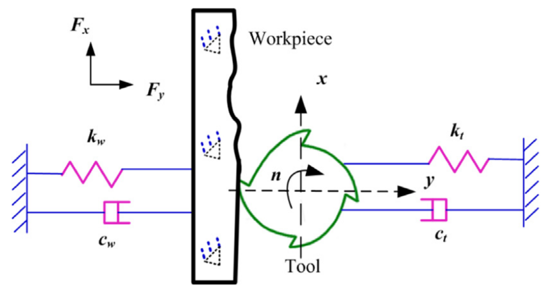

Fig. 2. Dynamic modeling of milling process.

Dry machining means that no cutting fluid is used during machining process for economic as well as environmental reasons. In this work, the experiments were performed under dry milling thin-wall titanium alloy Ti–6Al–4V. Variable pitch tool was used in order to decrease cutting vibration and cutting temperature, and uniform pitch tool is used to compare the experimental results. Furthermore, signal analysis methods of time domain, frequency domain and time-frequency domain of cutting forces and tool vibration displacements were used to analyze further vibration reduction mechanism of variable pitch tools.

2. Dynamics of the milling process for thin wall structure

2.1. Dynamic model

The tool body (tool/toolholder/machine) and workpiece are assumed to be flexible in milling thin-wall structure. A single degree of freedom milling system is shown in Fig. 2. Where, n is spindle speed, x and y denote the direction of feed and perpendicular to the machined surface. $F_x(t)$, $F_y(t)$ are cutting forces in the two directions. The governing equation of the milling process can be expressed by the following equation:

$$\begin{bmatrix} m_t \\ m_w \end{bmatrix} \begin{bmatrix} \ddot{y}_t \\ \ddot{y}_w \end{bmatrix}^T + \begin{bmatrix} c_t \\ c_w \end{bmatrix} \begin{bmatrix} \dot{y}_t \\ \dot{y}_w \end{bmatrix}^T + \begin{bmatrix} k_t \\ k_w \end{bmatrix} \begin{bmatrix} y_t \\ y_w \end{bmatrix}^T = F_y(t) \tag{1}$$

where, m_t, m_w are the modal mass of tool and workpiece; c_t, c_w are their modal damping coefficients; k_t, k_w are their elastic

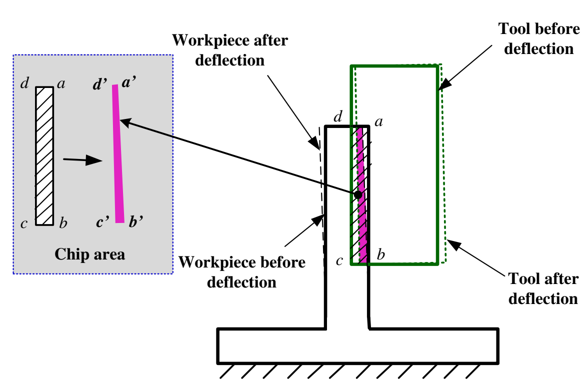

Fig. 3. Dynamic chip area of thin-wall structure in milling process.