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Energy Efficient Machining of Titanium Alloys by Controlling Cutting Temperature and Vibration

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Abstract

In this paper, a new approach is proposed to predict optimal machining conditions for most energy-efficient machining of Ti6Al4V. First an analytical cutting force model is implemented to predict the cutting forces and cutting power, followed by the temperature prediction to estimate the cutting temperature. Then based on the cutting temperature and stability lobes, the energy-efficient machining conditions are obtained. Thereafter experiments were performed to verify the simulation results by measuring forces with force gauges and cutting temperature using the tool-work thermocouple method. The case study shows that the proposed approach provides more stable cutting conditions as well as longer tool life using optimal cutting conditions by controlling vibration and the cutting temperature.

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Keywords: Energy-efficient machining, titanium alloys, cutting temperature, vibration

1. Introduction

Titanium alloys have recently been more widely used in the aerospace, biomedical and petroleum industries because of their good strength-to-weight ratio and superior corrosion resistance. As designers look to further improve their designs and as modeling technologies advance, industries are turning to titanium more often than ever. Figure 1 shows percentage of titanium parts used in airplane designs by year since 1950. The increasing use of titanium alloys magnifies the need for optimizing high-performance titanium machining.

The benefits of titanium alloys come at a price, however, because it is very difficult to machine them due to their poor machinability. Among all titanium alloys, Ti6Al4V is most widely used, which was also selected as the work material in this study. The thermal conductivity of Ti6Al4V titanium alloy is approximately 25 times and 10 times less than 7075 aluminum and WC-Co, respectively, as shown in Table 1 [1]. Such a low thermal conductivity of Ti6Al4V causes the cutting heat to remain at the tool/chip interface, rather than being conducted away into the workpiece and cutting chips for aluminum alloys, which is particularly problematic due to the fact that titanium has high chemical reactivity at elevated temperatures [2, 3]. This high cutting temperature then accelerates diffusive tool wear. Diffusive tool wear is one of the dominant wear patterns for WC-Co tools in titanium machining, which is typically characterized by diffusion of the tool material into the workpiece/chip. The diffusion wear is temperature dependent; high temperatures at the tool-chip interface favors tool wear occurring. Therefore, the maximum allowable cutting temperature places an upper bound on the allowable cutting speed to maintain a reasonable tool life while achieving the optimal combination of high productivity and low tool consumption.

Also the high strength of titanium alloys causes high cutting forces, and under high cutting forces chattering and vibration are more likely to occur [4]. It is necessary to select right cutting conditions to control cutting vibration and possible chattering. From a machining dynamics point of view, the stability lobes tend to recommend high rotational speed to avoid the chatter frequency. Even if there are large stable zones observed in stability lobe diagrams, the maximum available spindle speed is limited by cutting temperature in titanium machining.

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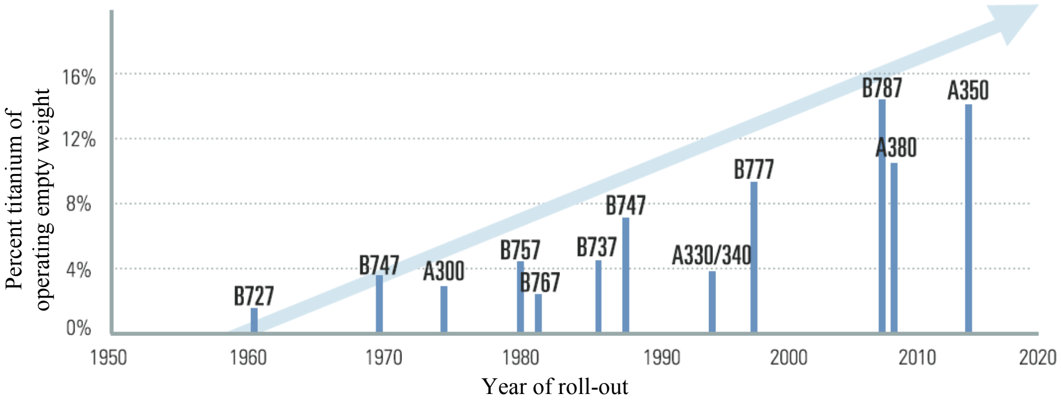

Fig. 1 The increasing use of titanium magnifies the need for optimizing high-performance titanium machining

Table 1. Properties of 3 widely used materials and WC tool material [1].

Material	Thermal conductivity (W/m-K)	Specific heat capacity (J/kg-C)	Tensile strength (MPa)
Aluminum 7075-O	173.	960	96.5
AISI 4340 steel	44.5	475	786
Ti6Al4V STA	6.7	526.3	1100
WC-Co (6%-10%)	60 - 80	200 - 400	1440

For almost all engineering materials, their yield strength is gradually reduced with the increase of temperature as shown in Fig. 2. Therefore, the higher the cutting temperature, the easier to remove the work material. Typically when the temperature reaches 800°C, the mechanical strength of WC is sharply reduced. Thus to control cutting temperature to soften the work material and maintain mechanical strength of tool materials is key to achieve energy-efficient machining of titanium alloys. A significant amount of work has been conducted on thermally assisted machining (TAM) with a great deal being focused on using a laser to deliver the thermal energy [5, 6]. The external heat source may lead to shorter tool life due to the premature degradation of cutting tools and accelerated diffusion and adhesion wear [6]. Thus in TAM effective cooling of cutting tools is necessary. Currently in practical industries, coolants are a must when carbide tools are used to cut titanium alloys, which makes it difficult to apply TAM, especially for milling operations. Ma et al [7] investigated the energy utilization and efficiency in TAM of a titanium alloy using numerical simulation. Their results show that preheating the workpiece reduces the cutting energy but increases the total energy in TAM. Thus there is significant potential to maximize total energy efficiency in TAM by optimal design of heating strategies and machining conditions.

Tool life and cutting speeds are major parameters which affect the efficiency of the machining process. The tool life rapidly reduces with an increase in the cutting speed [2]. Often in industry cutting tools and machine settings are chosen for different titanium alloys, without proper knowledge of the best combination of various cutting parameters [8, 9]. The objective of this paper is to propose a new approach to predict optimal machining conditions for most energy-efficient machining of Ti6Al4V.

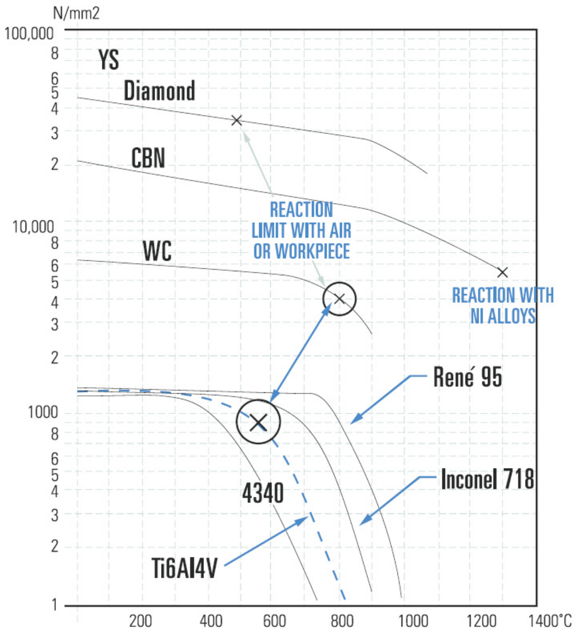

Fig. 2 Yield strength of tool and work material at different temperature [3]

2. Modeling of cutting forces and temperature

Oxley [10] developed a parallel-sided shear zone theory to predict cutting forces as shown in Fig. 3. Based on Oxley's theory, Wang et al [11] proposed a hybrid cutting force model by integrating the finite element analysis and Oxley theory to estimate the cutting forces and average temperature along the shear plane and at the tool/chip interface. The concept of the hybrid model was borrowed in this study to estimate the cutting forces. Instead of depending on the finite element method (FEM) simulation to get the shear angle, a pure analytical approach is used in this paper to predict the cutting force based on the equilibrium condition at the tool/chip interface as that stated in [10]. Based on the assumption that the shear flow stress k_{AB} along the shear plane is constant; the shear force F_S and cutting force F_C can be estimated as: