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Productivity Progression with Tool Wear in Titanium Milling

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Abstract
This paper presents experimental results for flank wear width, cutting force, temperature, and surface finish with increasing tool wear in titanium (Ti6Al4V) milling. The variation in these process indicators is presented for repeated trials as the wear progresses from a new tool condition to a significantly worn state. Based on the measured force data, cutting force coefficients are determined using a nonlinear optimization algorithm as the tool wears and these coefficients are combined with the structural dynamics to predict the process stability. The achievable chatter-free material removal rate is then computed for both the new and worn tool conditions. In this way, the variation in productivity is related to the wear state. As expected, the productivity reduces with increase wear.

Keywords: Milling, wear, force, temperature, surface finish, stability, chatter

1 Introduction

Titanium represents an important material for the aerospace and medical industries, as well as the automotive and energy fields. Subsequently, there is widespread interest in high productivity machining strategies. A significant limitation to high material removal rates when machining Ti6Al4V, a popular titanium alloy, is its low thermal conductivity. For comparison, Ti6Al4V conductivity is approximately 7 N/(s-ºC), while 1045 steel is 43 N/(s- ºC) and 7075-T6 aluminum is 140 N/(s-ºC) (Tlusty, 1999). Although the shear plane temperature is similar when machining Ti6Al4V and 1045 steel, the significant reduction in thermal conductivity for titanium causes the heat to be localized at the tool-chip interface and diffusive (temperature-driven) tool wear is accelerated. Because the cutting temperature tends to increase with cutting speed, low speeds are typically selected to ensure adequate tool life. These low cutting speeds result in relatively lower material removal rates (MRR).

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Titanium machining research efforts have studied, for example, tool wear mechanisms, including diffusion and adhesion thermo-chemical reactions (Hartung & Kramer, 1982), high speed cutting strategies (Abele & Fröhlich, 2008), and cryogenic machining (Hong et al., 2001). It has been observed that choosing cutting tools with many teeth (10 or more) can increase material removal rate while maintaining small feed per tooth values, low radial immersions, and high axial depths of cut. The associated challenge is efficient chip evaluation. The selection of tool paths that maintain a constant radial depth of cut has also been suggested to increase tool life (Zelenski, 2012). Other related tool wear evaluation efforts include Remadna & Rigal, 2006, Nouari & Ginting, 2006, Castejóna et al., 2007, Kuttolamadom et al. 2012a and 2012b, Sun et al., 2014, and Niaki et al., 2015.

In this paper, a study is described where the tool wear, cutting zone temperature, cutting force, and machined surface roughness were monitored over the life of a cutting tool while milling Ti6Al4V. The trends in these important process indicators are reported for multiple cutting trials. Additionally, the cutting force signal is used to estimate the cutting force coefficients by a nonlinear optimization approach as the tool wears. The change in force coefficients is used together with the system dynamics to identify the change in achievable MRR with wear state considering the limitation imposed by unstable machining conditions, or chatter. The paper is organized as follows. First, the experimental setup, which includes tool wear, temperature, force, and machined surface finish measurements, is detailed. Next, the nonlinear optimization procedure for cutting force coefficient determination is described. Then, the experimental results are presented and trends are highlighted. Finally, the MRR is calculated given the combined limitations imposed by tool wear and chatter.

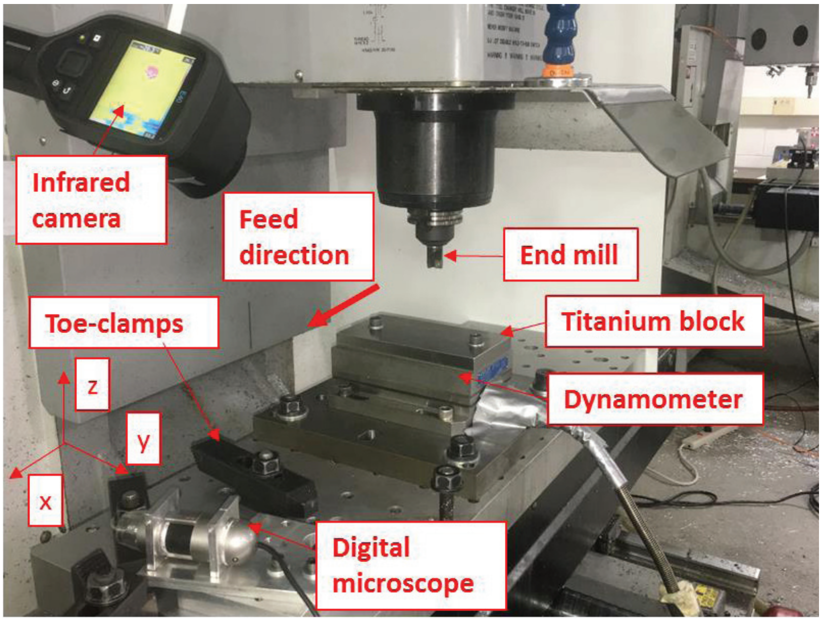

Figure 1. Setup for cutting force, tool wear, and temperature measurements using three-axis dynamometer, digital microscope, and infrared camera.

2 Experimental Setup

Cutting tests were performed on a Haas TM-1 computer numerically-controlled (CNC) vertical milling machine with a maximum spindle speed of 4000 rpm. The workpiece material was Ti6Al4V with approximate dimensions of 167 mm × 87 mm × 15.4 mm. The workpiece was rigidly fixed to a