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Effect of lubrication on machining response and dynamic instability in high-speed micromilling of Ti-6Al-4V☆

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ABSTRACT

The micromilling process is increasingly being used in biomedical, defence, electronics and aerospace industries for fabrication of miniaturized products of complex shapes. For difficult-to-cut materials like Ti alloys, limited stiffness of the micro-tool is a major impediment. This limitation can be overcome by using high rotational speeds which leads to reduction in chip load and, therefore, the cutting forces. However, high spindle speeds and low tool stiffness can render the process unstable due to dynamic variation in cutting forces. High speed micromilling of Ti6Al4V generates high temperature in cutting zone due to low thermal conductivity of Ti alloys which can also lead to a variation in cutting force and, hence, dynamic instability. Cutting fluid can play an important role because of its capacity to reduce friction and its ability to dissipate the heat generated between the micro tools and the workpiece. This study is focused on studying the effect of lubrication on the cutting forces and dynamic instability called chatter in high speed micromilling of Ti6Al4V. Experiments were carried out at different spindle speeds and feeds in both dry and lubricated condition. A significant reduction up to 38% in the cutting forces has been found in lubricated machining as compared with the dry machining. Two distinct regimes, lubrication sensitive (at rotational speeds >47,000 rpm) and lubrication insensitive (at rotational speeds <47,000 rpm) have been observed in this study. A critical spindle speed of 47,000 rpm has been identified which corresponds to the onset of lubrication dominant regime. To capture the effect of process mechanics, mechanistic force model using velocity-chip load dependent coefficients has been used to predict the forces and stability boundary. The predicted stability boundary limits have been compared with the experimental onset of chatter at four different spindle speeds. FFT spectrum analysis of acceleration of workpiece has been done to detect the process instability.

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1. Introduction

Micromilling is an extensively used fabrication technology in the precision manufacturing industry for telecommunications, electronics, defence and biomedical applications for creating complex 3-D miniature components with high relative accuracies. Ability of processing of wide range of materials, high quality surface finish and high material removal rate are its main advantage over other micro manufacturing technologies, such as lithography, micro EDM, laser ablation etc. [1].

Despite several advantages, there are some limitations and challenges with the micromilling operation. Due to growing push towards miniaturization, the diameter of the micro-end mill can be as low as few tens of microns which can result in orders of magnitude lower flexural stiffness as compared to the macro end mills. Due to this limited stiffness, micro-tool can undergo significant deflection and even catastrophic failure, especially, for difficult-to-cut materials like Ti alloys. This low flexural stiffness can be overcome by using high rotational speeds for reducing the chip loads (feed/flute) which can lead to a significant reduction in the cutting forces. High rotational speeds with limited stiffness could make the process susceptible to dynamic instability. This dynamic stability generally called chatter, a self-excited vibration, which can result in deterioration of surface finish and even catastrophic tool failure. Most common form of self-excited vibration is regenerative chatter which causes the instability in the cutting process.

High cutting speed usually increases the temperature in machining zone which can affect the process adversely, more so for low thermal conductivity materials, such as Ti alloys. This causes the heat to remain at the tool-chip interface and accelerates diffusive wear which result in cutting force variation. Friction between

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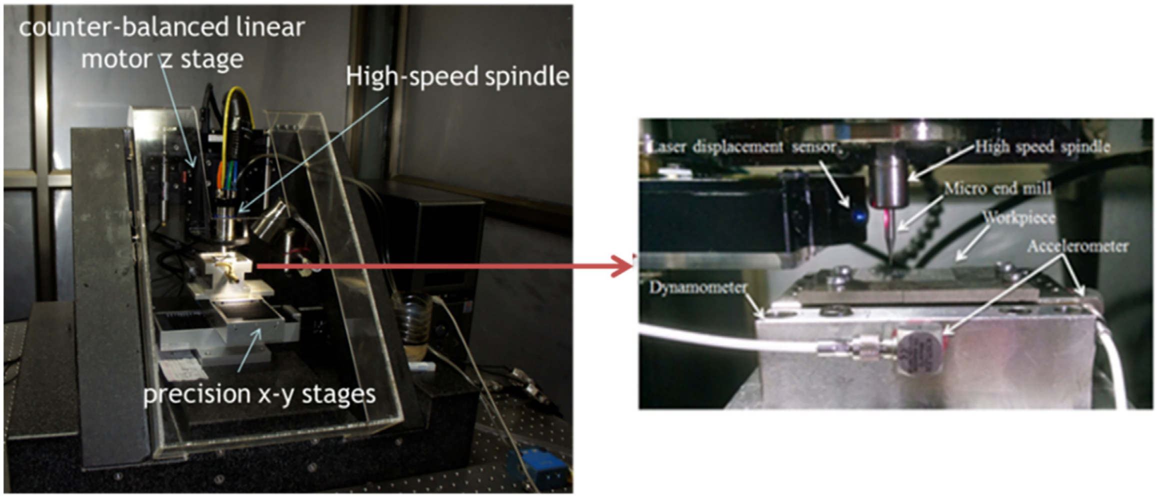

Fig. 1. High speed micromachining center.

the workpiece and cutting tool also affects the cutting forces. In the intermittent cutting operations, such as milling, especially at high-speeds, a large fluctuation in the cutting temperature could cause thermal cracks on the cutting edge and subsequently leading to the edge fracture of the cutting tool [2]. This variation in cutting forces due to friction and temperature can also induce dynamic instability of the system.

However, Wiercigroch and Krivtsov [3] have shown that friction between the tool and workpiece also affects the dynamics of cutting process and may cause self-excited vibration. Wiercigroch and Budak [4] have presented that the friction between the tool and workpiece and between the chip and tool is nonlinear function of relative velocity. Due to increased ploughing in micromachining, there is increased friction at the tool-workpiece interface [5]. The friction and adhesion between the chip and tool tends to be greater, which causes higher temperatures generating excessive tool wear [6].

To reduce the friction between micro end mill and workpiece surface and temperature in cutting zone, cutting fluid can be introduced to the system. Jun et al. [5] investigated the effect of cutting fluids on micro-milling. In addition to dry and MQL milling tests, they also studied the wet cutting in micro-end milling by means of applying large drops of the cutting fluid. Lower cutting forces and longer tool life were observed in MQL milling when compared to dry and flood cooling methods. As cutting zones are very tiny in micro milling, one of the most challenging aspects of the micromilling is effective cooling and/or lubricating. Vazquez et al. [7] studied the effect of cooling/lubricated conditions on Ti alloys in micromilling. Tool wear and surface roughness of machine surface were better in lubricated condition than dry machining. Yamazaki et al. [8] studied the effect of air cooling during turning of Ti-6Al-4V. They found that tool wear with air cooling was equivalent to that with minimal quantity lubrication (MQL).

As previously mentioned, the effect of lubrication on tool wear and surface topography in micromilling has been reported in the literature but the effect of lubrication on dynamic instability in high-speed micromilling process has yet to be studied. Hence, this paper is focused on investigating the effect of lubrication in high-speed micromachining on the process response and dynamic stability. Note that the direct jet impingement of the lubricant can result in the deflection of the micro end mill. Consequently, the direct jet impingement has been avoided in this work. The change state variables, such as stresses, strains, strain rates and temperature due to small undeformed chip thicknesses and high rotational speeds in micromilling operation needs to be accounted for accurate force and stability prediction. To phenomenologically model the variation in the material behavior, cutting velocity and chip load (feed/flute or maximum undeformed chip thickness) dependent cutting force coefficients have been determined for both dry and lubricated high speed micromilling of Ti-6Al-4V. These cutting coefficients have been used for mechanistic force modelling. Lubrication sensitive and insensitive speed regimes have been distinctly identified. It has been observed that beyond a critical rotational speed (47,000 rpm), the effect of lubrication is enhanced and results in reduced cutting forces and surface roughness along with improved stability limits. Stability lobe diagrams (SLD) have been generated to compare the stability limits in dry and lubricated micromilling. The effect of chip load on stability limits has also been studied.

2. Experimental work

2.1. Experimental setup

Experiments have been carried out on a high speed micromachining center developed in the Machine Tools Laboratory at IIT Bombay as shown in Fig. 1. The micromachining center has a high speed ceramic bearing spindle with a maximum speed of 140,000 rpm and average torque of ~4.3 N-cm. It is driven by AC synchronous electric motor having a variable frequency drive. The 3-axis micromachining center has stacked x-y stages with a positioning resolution of 0.5 μm and an accuracy of ±1 μm. The x-y stages are actuated by ball screw mechanism driven by a DC brushless servomotor. The z–stage has a linear motor with a positioning resolution of 5 nm which is pneumatically counterbalanced at two ends. All three stages are mounted on granite rigid structure. The whole micromachining center is placed on the vibration isolation table.

The workpiece has been fixed on the table top dynamometer (Kistler Minidyn 9256C1) to measure three component cutting force. Water soluble cutting fluid (Hocut 795H) with 10% concentration has been used for lubricated machining. Displacement of tool shank has been measured by using laser displacement sensor (Micro-Epsilon LD1607) which has sensitivity of 250 μm/10 V. Acceleration of workpiece in both feed and normal to feed directions has been measured by using accelerometer (Kistler 8640A50) which has the sensitivity of 97.3 mV/ g. All the measurement devices are connected to a data acquisition (NI DAQ) system.

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