Effects of Process Parameters On Tool Vibration And Force Transmissibility In High-Speed Micro-Milling Machine

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Abstract

High-speed micro-milling is an emerging technology used to produce micro and miniaturized products with smooth surface finish and high dimensional precision. However, tool vibration is a major problem in micro-milling as it directly affects the product accuracy, surface quality and tool life. Inappropriate selection of process parameters increases radial and axial thrust as well as force transmitted to structure during micro-machining which results in rapid tool vibration. This work focuses on the experimental investigation of process parameters (cutting speed and depth of cut) in order to reduce tool vibration due to axial and radial thrust in high-speed micro-milling. The tool used in this experiment is a 2-flute end mill cutter (1 mm cutter diameter) and workpiece is a commercially pure titanium (CpTi) plate. The operation was performed at different depth of cut and varying cutting speeds keeping the chip load constant. Vibration signals were acquired and processed to obtain the vibration thrust of the tool and the force transmitted to the structure. The results indicated that as the depth of cut and cutting speed increases, both axial as well as radial thrust decreases leading to lower vibration amplitude of the cutting tool and reduction in force transmitted to the machine structure.

1. Introduction

The extended demand of micro and miniaturized components has improved the growth of micro machining technology, especially micro-milling. High-speed micro-milling is an adaptable technology, capable to produce complex features over difficult to machine materials with mirror surface finish and dimensional precision. A design approach for ultra-precision high-speed micro-milling machine has been presented by Huo et al. [1-3] in their work. Das et al. [4] also developed a high-speed vibration free micro-milling machine. Certain aspects of micro-milling comprising of recent advances and future trends have been reviewed by Balazs et al. [5] in their study. However, tool vibration in high-speed micro-machining is a crucial problem which significantly affects the dimensional accuracy and surface finish. Due to low stiffness, the micro-milling cutters are subjected to severe vibration under the action of cutting force and thrust force which also resulted in tool damaging. Therefore, minimization of tool vibration is a challenging issue for high-speed micro-milling. Appropriate parametric optimization during high-speed micro-milling is highly essential in order to reduce tool vibration.

Several researchers tried to determine a stable machining condition in terms of low surface roughness and high tool life. Chen et al. [6] investigated that tool vibration increases with feed rate and depth of cut in precision milling. A stable machining condition was established at higher spindle speed. Therefore, better surface finish was found at low depth of cut, low feed rate and high spindle speed. Similar effects were determined by Bhogal et al. [7], in which it was found that tool vibration increases at high cutting speed, feed rate and depth of cut. However, in case of micro-milling peculiar effects were observed.

Rahman et al. [8] determined that tool enhances with increase in depth of cut and reduction in cutting speed, however, feed force and radial force was found to increase with increase in feed rate and depth of cut. At low feed rate, due to elastic recovery, significant vibration is induced and may be further minimized

by reducing the depth of cut [9]. The optimization of proper machining parameters in micro-milling to reduce tool wear, tool vibration and cutting and thrust force is a highly essential. For this, Malekian et al. [10] developed several tool wear monitoring technologies for micro-milling in order to maintain product accuracy and tool life. Feed rate is the most important parameter for cutting force in micro-milling, which if increases is desirable for stable machining condition. Additionally, low feed rate results in ploughing effect, elastic recovery of the work material and hence, chatter is often seen [11]. Park and Rahnama [12] developed a chatter stability model based on parametric changing in order to reduce chatters in micro-milling. Wang et al. [13] determined better process damping effect at lower cutting speed (Spindle speed below 20000 rpm), however at higher speed low, depth of cut was favorable in order to achieve low vibration in micro-milling. Proper selection of feed rate and depth of cut is a much-needed criteria to reduce built up edge and improve surface quality [14].

Lu et al. [15] observed that increase in feed rate and depth of cut enhances the surface roughness of the machined product. In order to minimize tool vibration, low depth of cut is favorable for lower spindle speed (40000 rpm to 70000 rpm). However, for machining with higher depth of cut, the machine needs to be operated at higher spindle speed (above 70000 rpm) [16]. Zhang et al. [17] investigated that tool vibration is a significant source for reduction in cutting force in micro-milling. Therefore, feed rate should be low in micro-milling in order to minimize cutting and thrust forces during micro-milling for reduced tool vibration [18]. Similarly cutting force increases with cutting speed, however, this phenomenon is only observed during low-speed operation (spindle rotational speed below 5000 rpm).

However, the effect of process parameters (especially depth of cut) over the axial thrust force is still undetermined for high-speed micro-milling operation. The axial thrust results in tool vibration in axial direction. It deteriorates the surface finish and tool wear during high-speed machining of hard materials. This work focused on the experimental investigation of process parameters (cutting speed and depth of cut) in order to reduce tool vibration due to axial thrust in high-speed micro-milling. A 2-flute end milling cutter (1 mm cutter diameter) was used to cut a commercially available pure titanium plate of 5 mm thickness. The operation was performed at different depth of cut and varying cutting speeds keeping the chip load constant. Vibration signals were acquired and processed to obtain the axial vibration of the tool.

This paper provides a brief introduction of axial and radial thrust due to tool vibration in the first section. The methodology used has been discussed in the second section. The third section provides the results obtained from experiments and a discussion of the results. The fourth section is comprised of the comparative study of the obtained results Finally, the conclusions have been provided in fifth section.

2. Methodology

This work is based on the experimental vibration and force analysis of a two-flute milling cutter due to variation in depth of cut. The experiments were performed on CNC operated high-speed micro-milling center with a two-flute milling cutter mounted on the spindle. The maximum rotational speed of the

spindle is 60000 rpm. For the experiments, a micro-milling cutter was mounted on the spindle of the micro-milling setup which is shown in Fig. 1. Machining was performed over a plate of commercial pure titanium (CpTi) with cross-section of 25 mm x 25mm and 5mm thickness. The tool used was a 1 mm diameter 2 flutes milling cutter of AlTiN coated tungsten carbide made by Axis microtools. The operating conditions were varied by varying the cutting speed, operating frequency, feed rate and depth of cut. The operating frequency was varied from 200 Hz to 700 Hz at intervals of 100 Hz for three different feed rates and depth of cut for each set of experiments. The three different feed rates (mm/min) were 48, 120 and 180. The depth of cut was 50, 75 and 100 μm . The three different levels of cutting speeds were 37.7, 94.24 and 141.36m/min.

The chip load is taken constant and 2 μm for each experiment. The chip load can be calculated from the formula, $(L = f/NZ) = 2 \mu\text{m}$. Where, Z is the number of flutes; f is the feed rate and N is the rpm of the spindle. Therefore, with increase in RPM, the feed rate was also increased to maintain the chip load as constant. For a particular cutting speed, the vibration signals have been taken for different depths of cut.

Spindle speed of 200 Hz was selected because it is the resonance condition of the system under the action of cutting force. The vibration data at 200 Hz signifies the effect of resonance on axial and radial vibration of the tool.

The vibration signals were acquired using two uniaxial accelerometers mounted in axial and radial directions on the spindle. A force transducer was used to acquire the signals of force transmitted to the structure. The data was acquired using Bruel and Kjaer RT Photon pro 4 channel analyzer. These acquired data were then processed in ME-Scope software to obtain the vibration amplitude for each operating condition. The thrust force acts in the axial direction of the spindle. Hence the amplitude of tool vibration along the axial direction signifies the movement due to the action of thrust force. Any change in amplitude due to changing the depth of cut specifies the effect of depth of cut on axial thrust force during machining. The vibration amplitude in radial direction signifies the lateral vibrations of tool. These vibrations can lead to irregular features on the workpiece. Hence, it is essential that radial vibration should be low. The force transmitted to the support structure signifies the stability of the structure. Lower forces signify higher stability and hence, higher efficiency of machining and increased tool life.

3. Results And Discussion

The vibration spectra for axial direction obtained from the experiments on micro-milling machine have been shown in figure 2. The variation in vibration amplitude due to changes in depth of cut and cutting speed are also represented. The above figure represents the frequency spectrum of axial direction obtained at different cutting speeds and depth of cut. Figure 2 (a) is the frequency spectrum for 50 μm depth of cut at varying operating frequencies of the micro-milling machine. Similar frequency spectrums for 75 μm depth of cut and 100 μm depth of cut are shown in figures 2(b) and 2(c) respectively. The arrows on the graph represent the direction in measurement was taken. It was observed that the axial tool vibration decreases with increase in cutting speed. This is expected because stable cutting condition is

established at higher cutting speeds in micro-milling. As per the previous literatures, cutting force reduces with increase in cutting speed during high-speed micro-milling. Therefore, a smooth cutting condition will be developed at higher operating frequency of spindle, resulting in reduction in axial thrust and axial tool vibration. It is confirmed that for the same depth of cut, the vibration amplitude is the maximum when operating frequency is equal to the resonance condition of the system. It is also observed that the vibration is lowest for maximum operating frequency. The vibration spectra for radial direction obtained from the experiments on micro-milling machine have been shown in figure 3. The variation in vibration amplitude due to changes in depth of cut and cutting speed are also represented. The above figure represents the frequency spectrum of axial direction obtained at different cutting speeds and depth of cut. The trend of radial vibration is similar to that of axial vibration. The arrows on the graph represent the direction in measurement was taken. But it can be observed that the vibration amplitude in radial direction is higher as compared to axial direction. This is due to the fact that during machining, the load is on the spindle and spindle holder and thereby reducing its movement. Hence, the vibration amplitude in axial direction is lower than the vibration amplitude in radial direction. Moreover, higher vibration amplitude in axial direction will lead to improper depth of cut and thus poor feature generation and surface finish on the workpiece. Hence, lower vibration amplitude in axial direction is desirable. The spectra for force transmitted to the structure obtained from the experiments on micro-milling machine have been shown in figure 4. The variation in force transmitted due to changes in depth of cut and cutting speed are also represented. The above figure represents the frequency spectrum for force transmitted to the structure of the micro-milling machine at different cutting speeds and depth of cut. It was observed that the force transmitted decreases with the increase in depth of cut. Apart from a peak at 200Hz, two peaks at 400Hz and 600 Hz are also observed. These peaks can occur due to the probable occurrence of second and third natural frequencies of the system. However, this has not been confirmed in the present study.

4. Comparative Study

A comparative study of the variation in axial and radial vibrations and the force transmitted to machine structure has been presented in this section.

Figure 5 represents a comparative analysis of the variation in axial vibrations with different depth of cut and cutting speed.

It can be observed from figure 5 and that as the depth of cut increases, the tool vibration decreases along the axial as well as radial direction. At higher depth of cut large amount of heat accumulation takes place in the cutting zone. This is due to increase in material removal rate which leads to increase in cutting force and cutting power consumption as well. Low thermal conductivity of titanium does not tend the accumulated heat to dissipate. Therefore, a localized heating zone was induced over the workpiece surface resulted in thermal softening of the workpiece at the cutting area. As the depth of cut increases, more thermal softening occurs at the cutting zone. Therefore, the axial and radial thrust was reduced at higher depth of cut. This condition developed a stable machining condition with less amount of chatter.

Additionally, when the depth of cut is small, the tool is just ploughing over the surface depending upon the tool cutting edge radius and results chatter formation during machining. This effect increases the axial and radial thrust on the cutting tool, resulted in higher tool vibration. On the contrary, for a larger depth of cut, the cutting tool penetrates the surface which results in better grip of tool on the workpiece and thus lower vibration amplitude.

It can also be observed that the vibration amplitude in radial direction at any particular frequency and depth of cut is higher than the vibration in axial direction. This is due to the fact that the load on the spindle is in axial direction resulting in more stability along z axis. Moreover, the rotation of spindle causes slightly higher vibration amplitude along the radial direction. Lower axial vibrations lead to better finish and feature generation in the workpiece. Hence, lower axial vibration is desirable.

It can be observed from figure 7 that the force transmitted to the machine structure decreases with increase in depth of cut. Higher depth of cut leads to lower vibration amplitude and thus lower force is transmitted to the machine structure.

Lower tool vibration and low force transmission leads to higher stability, higher tool life, better surface finish and less noisy operation. Therefore, in order to achieve quality surface finish with improved tool life, the machining should be at high speed and considerably higher depth of cut depending upon the cutting-edge radius of the milling cutter during high-speed micro-milling operation is recommended based on this study.

5. Conclusion

The work was focused on the experimental investigation of process parameters (cutting speed and depth of cut) in order to reduce tool vibration and force transmitted to machine structure in high-speed micro-milling operation. A 2-flute end milling cutter (1 mm cutter diameter) was used to cut a commercially available pure titanium plate of 5 mm thickness. The operation was performed at different depth of cut and varying cutting speeds keeping the chip load constant. Vibration and force signals were acquired and processed to obtain the axial and radial vibration of the tool and the force transmitted to the machine structure. The results indicated that as the depth of cut increases, the thrust decreases leading to lower vibration amplitude in both axial as well as radial direction. Similar phenomenon was observed in case of cutting speed also. The force transmitted to the machine structure was also observed to decrease with increase in depth of cut. Therefore, higher depth of cut (depending on tool cutting edge radius) at higher cutting speed develops a stable machining condition. This also leads to a better surface finish, stable machining operation, less tool wear, increased tool life and reduced chatter.

Declarations

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Declaration of Conflict of Interest

The authors declare they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Figures

Figure 1

Experimental setup

Figure 2

Spectra for axial vibration for depth of cut of (a) 50 μm ; (b) 75 μm ; and (c) 100 μm

Figure 3

Spectra for radial vibration for depth of cut of (a) 50 μm ; (b) 75 μm ; and (c) 100 μm

Figure 4

Spectra for force transmitted for depth of cut of (a) 50 μm ; (b) 75 μm ; and (c) 100 μm

Figure 5

Tool vibration amplitude in axial direction for different depth of cut and operating frequency of spindle

Figure 6

Tool vibration amplitude in axial direction for different depth of cut and operating frequency of spindle

Figure 7

Force transmitted to machine structure for different depth of cut and operating frequency of spindle