Experimental investigation on burr formation in vibration assisted micro milling of Ti-6Al-4V

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Abstract: Titanium alloys have been widely used in aerospace, marine and medical industries, due to their high strength, good corrosion resistance and excellent heat resistance. High tool wear rate and low machining accuracy limits conventional micro milling to meet increasing stringent demand. In this paper, a prototype of two directional vibration stage and its control system are developed for non-resonant mode vibration assisted micro milling system. A series of slot milling experiments are carried out to investigate the effects of vibration parameters on burr generation. The results show that vibration- assisted micro milling is an effective way to reduce burr size when choosing appropriate vibration parameters and directions.

Keywords: vibration assisted machining, vibration assisted milling, micro-milling, burr formation, Ti-6Al-4V

1. Introduction

Burr formation, similar to chip generation, is a common phenomenon in the machining process and one of the important criteria for the evaluation of the machined surface. Burrs are caused by the material plastic deformation at the end of cutting process and are affected by many factors including cutting parameters, tool geometry and material properties [1]. Presence of burrs affect product life cycle and machining accuracy, and also pose a risk to operators. Therefore, an extra deburring or edge finishing process is usually needed, which is costly and inefficient. Moreover, the deburring process may introduce unwanted residual stress and even damage the parts.

With the development of miniaturization technology, miniature components are in increasing demand in various applications such as optical, electronic and biomedical industries. As an important micro manufacturing method, micro end milling is capable of manufacturing micro products with complex features across a wide range of materials. Burr formation in micro milling process is much more complicated compared with its macro scale counterpart because of the well-known size effect, e.g. cutting edge radius can be no longer ignored [2]. The machining performance can be influenced by the tool edge radius when undeformed chip thickness is small enough. It has been reported that the ratio of undeformed chip thickness to cutting edge radius is closely linked with machining surface ploughing effect, effective rake angle and specific cutting energy, which in turn impacts the burr size, surface quality and tool wear [3-4]. Moreover, many other factors that can affect burrs formation has been reported. Kou et al. [5] pointed that the negative shear force on micro milling cutter affects burr size greatly and the machining process can be improved by enhancing workpiece rigidity. Schaller et al. [6] studied the effect of material differences on burr formation and found that materials with higher ductility property enhance burr generation. Lekkala et al. [7] investigated the effect of different processing and tool parameters though ANOVA method and found that burr size can be reduced by increasing feed rate and the number of flutes of cutting tools.

Vibration assisted micro machining (VAMM) is a precision machining process which combines micro end milling with small amplitude high frequency displacement either on tool or workpiece. It produces a periodic separation between uncut workpiece and the tool. This can decrease the average machining forces, reduce tool wear and generate certain surface textures [8-10]. In addition, it is also proved to reduce burr generation. Ding et al. [11] investigated the influence on top burrs formation in a two-dimensional vibration micro end milling process. According to their research, the two ratios, undeformed chip thickness to the cutting edge radius (RTR) and the time when undeformed chip thickness less than the minimum chip thickness to the total processing time (RTT), have a crucial impact on the burr formation. By comparing the machining results and simulation data, they found that both RTR and RTT were decreased with

the increase of the feed rate, which led to a decrease of top burr height. Furthermore, utilizing vibration on the workpiece with suitable vibration parameters can decrease the height of top burrs and obtain a better cutting performance because of RTT reduction. Ti-6Al-4V has a wide application in aerospace and medical fields due to its high strength, low density, high temperature resistance, high corrosion resistance and good biocompatibility [12]. However, the drawbacks, for instance, hard to machine, keep it at a high manufacturing cost. In this study, a prototype two dimensional non-resonant vibration stage that draws on previous designs is developed. Slot milling experiments with vibration assistance are conducted on Ti-6Al-4V with different vibration parameters. The machining results in terms of burr size are evaluated by scanning electron microscope (SEM), and the influence of vibration parameters on top burr size are investigated.

2. Burr types and material removal mechanisms

2.1 Types of burrs in micro end milling

Burrs are described by many factors such as material properties, manufacturing processes and shapes. Currently, two different approaches are commonly accepted by researchers for burr descriptions in micro end milling. In terms of burr formation, four types of machining burrs can be categorised: rollover burr, tear burr, cut-off burr and Poisson burr, as shown in Fig. 1. The rollover burr is a kind of bended chip which is also called exit burr because it is usually formed at the end of processing. The tear burr is not the shearing clearing result, rather it is caused by the result of material tearing loose from the workpiece which is much like the burr formation in punching process. The cut-off burr is the consequence of workpiece falling apart from raw material before cutting process is finished. The Poisson burr is a result of the material's tendency to bulge to the sides when it is compressed until permanent plastic deformation occurs. Another burr description is according to burr shapes, burr locations and burr formation mechanisms [13]. Fig.2 shows the burrs types in face milling process which includes entrance burr, exit burr, side burr and top burr. The exit burr is defined as a burr attached

to machined edge at the end of milling. The side burr adheres to the transition surface and top burr appears to the top surface of the workpiece [14].

Figure 1 Schematics of Poisson burr, tear burr and rollover burr

Figure 2 Types of burrs in micro end milling

2.2 Materials removal in micro end milling

According to the relationship between the uncut chip thickness H and the minimum chip thickness H_c which is largely determined by machining parameters, inherent material properties and cutter edge radius, the circumstances of micro milling process can be divided into three types as shown in Fig.3. When the uncut chip thickness is

smaller than the minimum chip thickness, as shown in Fig.3a), there are no chips formed and only plastic-elastic deformation occurs in the cutting area, which intensifies the ploughing effect and tool wear [15]. Chips start to form when uncut chip thickness reaches the minimum chip thickness, as shown in Fig.3b). When the uncut chip thickness is comparable to the minimum chip thickness, a mixed deformation type which combines plastic-elastic and shear deformation happens in the cutting zone. As the uncut chip thickness increases to minimum chip thickness, as shown in Fig.3c), workpiece material is removed by the cutter as a chip, and the elastic recovery becomes very small and negligible. In this process, the surface finish quality, tool life, surface roughness and burr formation could be improved by increasing uncut chip thickness. The effect of minimum chip thickness is unavoidable in a slot milling process. However, by applying the vibration into the micro milling process, the process stability can be improved because the instantaneous uncut chip thickness and cutting speed is changed significantly compared with the conventional micro milling, especially in the cutting in and cutting out area.

Figure 3 Material removal mechanism in micro end milling process

3. Vibration stage design

Vibration stage has a considerable influence on the performance of a VAMM system. To obtain the desirable performance, several prototypes of VAM stages were developed. Zhang et al. [16] developed a vibration stage for studying cutting forces by analyzing the two different VAMM situations (tool and workpiece periodic separated and unseparated). It can be achieved by changing the combination of vibration

parameters and cutting parameters. However, the operating frequency and amplitude of the designed platform are fixed at 19.58 kHz and 8 μm respectively. An improved 2D vibration stage design was proposed by Ibrahim et al. [17]. It features a compact structure with overall dimension only 50×50×15mm and a higher operating frequency (from 1000 - 3000 Hz), which allows more cutting parameter combinations. However, only low frequency vibration can be generated by the platform and small platform size limits the workpiece shape and size. Chern and Chang [18] devised a 2D vibration stage by combining piezoelectric actuators, springs and slideways, but it also required a high-precision installation process.

As shown in Fig.4, a novel structure of 2D vibration stage with wide working frequency range (from 0 Hz to 10 kHz) and high unloaded vibration displacement (up to 20 μm) is proposed in this paper [19]. Piezoelectric actuators which can convert electrical energy to linear motion are selected as the vibration source due to its high precision, strong driving force and fast response. They are mounted in x and y directions which can generate hundreds of push or pull force and controlled by a LabVIEW program based on the data acquisition card and amplifier. Double layer flexure hinges are adopted in the stage structure to reduce the x and y direction couple effect and make the whole transmission process more effective.

Figure 4 Schematic diagram of vibrating stage

Figure 5 Layout of experiment equipment

4. Experimental setup

The experiments are conducted on desktop precision micro milling machine (Nanowave MTS5R) which is equipped with a high speed spindle (max 80,000 rpm). Fig.5 shows the designed vibration stage is mounted on the machine tool. Slot milling experiments are carried out on Ti-6Al-4V using 1 mm diameter uncoated carbide end mills. The cutting edge radius of the tools is measured approx. 3 μm on the effects of vibration frequency and vibration direction are investigated. The experimental machining and vibration parameters are listed in Table 1.

Table 1 vibration and cutting parameters

NO.	Amplitude (μm)	Frequency (Hz)	Spindle Speed (rpm)	Feed rate (mm/min)	Vibration Direction
1	0	0	20000	50	NA
2	1	400	20000	50	x (feed direction)
3	1	4000	20000	50	x (feed direction)
4	1	9000	20000	50	x (feed direction)
5	1	400	20000	50	xy (feed and cross feed direction)
6	1	4000	20000	50	xy (feed and cross feed direction)
7	1	9000	20000	50	xy (feed and cross feed direction)

5. Results and discussion

To investigate the machining burr formation under different vibration parameters, machining experiments are conducted with a left to right feed direction, and all machining surfaces are checked by a SEM (TM3030, Hitachi) and the testing results illustrate that burr is always smaller on up milling side for all vibration parameters. Fig. 6 shows a comparison between typical machined slots by conventional and vibration assisted micro milling respectively. Large top burrs can be found on the workpiece machined by conventional micro milling on both up milling and down milling sides. More machining tearing burrs appear on the down milling side compared with up milling side and this phenomenon can be explained through analyzing the slot milling process. As the cutter is engaged to the workpiece, the workpiece material is squeezed and pushed in up milling side first. As the process going on, the uncut chip thickness increases, which enhances support effect on the uncut materials and the shear action on material removal. However, on down milling side, the support effect of uncut material is smaller than that on up milling side, and hence the uncut materials are pushed out of the top of down milling side and large irregular tearing burrs are generated on this side. It can be hard to remove these burrs due to the small feature size and influence the accuracy of the milling slot. While in vibration assisted micro milling, no large top burr can be found on both sides. Since vibration is superimposed to the process, the motion of tool tip becomes to reciprocating (one dimensional VAMM) or elliptical (two dimensional VAMM). This leads to a periodic separation between tool tip and the workpiece. As a result, the down milling and up milling can occur on both sides of the slot alternatively [20]. In addition, material removal mode changes from shear dominated deformation in conventional micro milling process to a mixed action that combines dynamic impact and shear deformation in VAMM, and the ploughing/rubbing between workpiece and cutter is also reduced. As a consequence, the cutting force and discontinued chips can be reduced, which in turn reduce the burr generation and improve machining accuracy. Fig. 6 (b) shows improved slot edge quality from VAMM.

Figure 6 Machining results comparison between (a) conventional micro end milling and (b) vibration assisted micro end milling

Fig. 7 shows the enlarge images on down milling side for tear burr observation, by comparing the results of (a)(b), (c)(d) and (e)(f), it can be seen when vibration frequency is constant, the tear burr size is reduced as adding cross feed direction vibration to the process, that is due to tool tip cutting direction has been changed slightly and enhance material tearing loose from the workpiece [21]. In addition, a trend of reduced tear burr can be found when increasing vibration frequency under same vibration direction. As the tool vibration frequency increases from 400 Hz to 8000 Hz, the tool vibration speed is enhanced, this leads to an increase in reciprocating cutting on down milling side and large tear burr is removed. As a result, the tear burr size can be reduced.

Figure 7 Down milling side tear burr results with different parameters: (a) Feed direction vibration with a frequency of 400Hz. (b) Feed and cross direction vibration with a frequency of 400Hz. (c) Feed direction vibration with a frequency of 4000Hz. (d) Feed and cross direction vibration with a frequency of 4000Hz. (e) Feed direction vibration with a frequency of 8000Hz. (f) Feed and cross direction vibration with a frequency of 8000Hz.

In order to assess the top burr height precisely, the maximum top burr height h was measured as shown in Fig. 8. The variation of top burr height results with the vibration frequency for two vibration modes (feed direction and feed and cross feed direction) are shown in Fig. 9. It demonstrates that the top burr height in both vibration modes of VAMM is always smaller than that in the conventional micro milling, which indicates that the VAMM is an effective way to reduce top burr generation. Fig 9 (a) shows the top burr height variation for both up milling and down milling sides between conventional micro end milling and the feed direction VAMM. The maximum burr

height in conventional micro milling is around 36 μm on the down milling side and 28 μm on the up milling side. As vibration is applied to the process, the top burr height will be reduced by 58% to 82% on up milling side and nearly 50% on down milling side depending on the parameters. Moreover, higher vibration frequency has a positive effect on burr height reduction. The higher vibration frequency, the lower top burr height can be obtained. That is due to the intermittent cutting effect. As the vibration frequency increases, the critical upfeed velocity V_{crit} (Eq. 1) can be larger than upfeed velocity of micro end milling, and a less average cutting force and less cutting heat can be generated. This reduces the instantaneous compressive and bending stresses in the cutting deformation zone and decreases the ploughing/rubbing effect between cutting tool and workpiece. As a result, top burr high is reduced.

$$V_{crit} = 2\pi fA \quad (1)$$

Where: f is the vibration frequency

A is the vibration amplitude

Fig. 9(b) shows the top burr height variation results for 2D VAMM. The burr height in 2D VAMM is also reduced but there is not much improvement compared to the 1D VAMM. **There is no effect on the critical upfeed velocity V_{crit} when cross-feed direction vibration is added to the cutting process and the top burr reduction is mainly contributed by feed direction vibration in the 2D VAMM process.** It can be concluded that the vibration in cross-feed direction has little effects on the top burr height reduction in slot milling process. As the vibration in cross-feed direction not changes the cutting trajectory between the cutter and the workpiece during the material removal process, it almost has no positive effects on the top burr reduction. For some specific parameters the top burr height is even larger than that in 1D VAMM. The top burr height in down milling side increases almost 3 μm when vibration frequency changes from 400Hz to 4000Hz and both up milling and down milling side burr height reach the lowest value at the frequency of 8000Hz which is 6 μm and 13 μm , respectively.

Figure 8 Top burr height measurement

Figure 9 Burr height measurement results, (a) feed direction vibration assisted micro milling, (b) feed and cross feed direction vibration assisted micro milling

6. Conclusion

In this paper, vibration assisted micro milling experiments are performed on Ti-6Al-4V workpiece using a two dimensional vibration stage developed. The following conclusions can be drawn:

- 1) With appropriate machining and vibration parameters, vibration assisted micro milling can reduce tearing burr formation, especially on the down milling side. In the micro milling with vibration assistance, up milling and down milling can occur in both sides of the slot.
- 2) Vibration assisted milling produces very small top burr size compared with conventional micro milling, this is due to the former can reduce average cutting force and decrease the ploughing/rubbing between workpiece and cutter.
- 3) The vibration direction has significant influence on the burr reduction, and the vibration applied in feed direction has better effect than cross-feed direction.
- 4) Both frequency and vibration directions affect the top burr height. Generally higher vibration frequency helps minimize burr formation, although more systematic investigation will be carried on optimizing the machining/vibration parameter.

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