Micro-milling of Pyramid Structured Surface for Implant Application

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Abstract: Surface modification, as a promising approach to improve biocompatibility of biomaterials, has captured extensive close attention among many researchers. Here, micro-milling technology was used in constructing pyramid micro-structures on the surface of Ti-6Al-4V implant. Cutting parameters, including spindle speed, feed rate and depth of cut, were optimized to control the generation of burrs. In addition, low melting point alloy was selected to extend the boundary of the workpiece as supporting material to prevent the generation of top burrs. The surface topographies were characterized using scanning electron microscope and laser scanning microscope. Results showed that the dimension of burrs decreased with the decrease of depth of cut, and the size of burrs decreased with the increase of feed rate. Moreover, burrs nearly not appeared on both sides of the micro-grooves machined with low melting point alloy (LMPA) coating. Pyramid micro-structure on the workpiece surface was built successfully by combining optimized cutting parameters (S=35 kr/min, V_f=60 mm/min, a_p=5 μm) and LMPA coating.

Key words: micro-milling; micro-groove; burr; parameters optimization

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0 Introduction

Biological implant materials are widely used for replacing damaged or diseased tissues[1-3]. Owing to good mechanical properties and biocompatibility, titanium and titanium alloy are regarded as main implants in biomedical fields[4-6]. Surface topography, as one of the most important factors on osseointegration, has attracted the interest of many researchers[7]. Micro-groove can provide a stable growth environment for fibrin blood clot and prevent fibrin blood clot falling off. In addition, the biological activity of osteoblasts could be affected by micro-groove which promoted the bone integration fast and steadily[8]. Therefore, many scholars pay close attention to the surface modification of titanium alloy in order to improve its biological properties.

Micro-milling can be in use for manufacturing the micro-scale structure on the implant surface. Until now, various kinds of surface modification technologies have been utilized in modifying the surface characteristic to enhance biological activity and long-term survival of biomedical implants, such as sandblasting, photolithography, laser cladding, ion coating and chemical processing[9-12]. However, the chemical composition and the micro-structures of the surface are difficult to control precisely. Sometimes the coating was easy to fall off, for example the ion spraying coating[13]. The cracks caused by laser on the implant surface were bad to biocompatibility. Micro-milling technique is an efficient approach to obtain designed micro-structures without changing the fine properties of implant surface compared with others. Based on the aforementioned considerations, the method for obtaining micro-structure by micro-milling is presented here. The

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micro-milling is different from traditional milling operation, which has an effect on the surface generation process [14-15].

Previous studies have shown that the micro-grooves and pyramid micro-structures were helpful for osteoblasts adhesion and differentiation[16-17]. Moreover, these kinds of structure could affect the biological behavior of bone cells and promote the stability of osseointegration[18]. However, in micro-milling process, it is difficult to control and remove burrs during or after the machining process. The traditional methods to prevent burrs couldn't be properly applied on micro-burrs removal. In micro-milling process, there were many factors affecting the burr formation such as tool shape, geometry parameters, cutting parameters, cutting methods and properties of workpiece material, etc.. Fig. 1 shows the micro scale milling process using V-shaped tool. A large number of scholars had in-depth studies on the burr problem in micro-milling. Schmidt[19] found that the burrs were larger in the side of down milling, and the size of burr was slightly smaller with the increase of cutting speed. Kishimoto[20] had studied the formation of the retroflex burr in the process of face milling, and stated that secondary burr formed more easily in the large plastic deformation. Lee et al. [21] had found that the size of burr became larger with depth of cut and feed speed increasing.

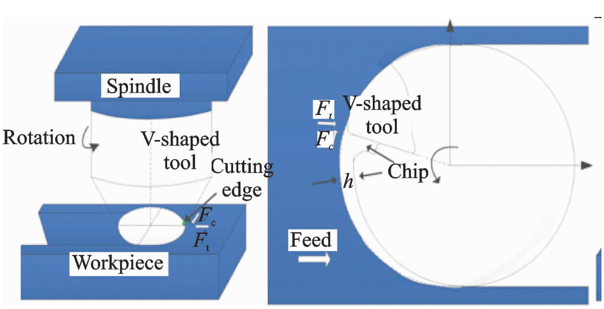

Fig. 1 Simplifications for micro-milling process

Here, the pyramid micro-structure was obtained on the surface titanium alloy by micro-milling. Meantime, the burrs were controlled and removed through optimizing cutting parameters and adding auxiliary support.

1 Experiments

1.1 Material pretreatment and experimental setup

The workpiece was fabricated from medical titanium alloy Ti-6Al-4V, which has good comprehensive performance including higher intensity, smaller elastic modulus and lower heat conductivity. The polished samples of Ti-6Al-4V with a dimension of 20 mm×10 mm×10 mm are used in the present work.

The micro-milling experiments were conducted using a five-axis micro machining center, as shown in Fig. 2. The maximum rotational speed was 50 000 r/min and axis travels were 250 mm for X, 220 mm for Y, 250 mm for Z, respectively. It was equipped with a laser Control NT for measuring micro-milling tools.

The micro-milling cutters used in the experiments were V-shaped cutter made in Swiss. A shank diameter of ∅3 mm was used to fit the spindle collet, with its length of 40 mm. The micro-milling cutter is shown in Fig. 2.

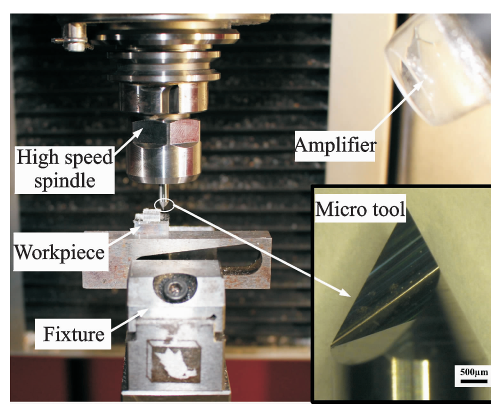

Fig. 2 Micro-milling machine and tools used in micro-milling experiments

1.2 Cutting parameters optimization and supporting material coating

To examine the effect of cutting parameters on the formation of burrs in micro-milling process, micro-grooves with dimension of 20 μm in depth were machined. The selected controllable factors that affect burrs formation are spindle speed, feed rate and depth of cut. The different cutting parameters are designed via orthogonal test shown in Table 1.

Table 1 Cutting parameters in micro-milling

No.	Spindle speed S/(kr · min^{-1})	Feed rate V_f/(mm · min^{-1})	Depth of cut a_p/μm
1	25	20	7
2	25	40	7
3	25	60	7
4	25	20	5
5	25	40	5
6	25	60	5
7	35	20	7
8	35	40	7
9	35	60	7
10	35	20	5
11	35	40	5
12	35	60	5

In this study, 70 ℃ low melting point alloy (LMPA) was used as supporting material, which was daubed on the surface of workpiece with the thickness of 0.3 mm to form a closed thin layer on sample surface. After LMPA was solidified, the micro-grooves were machined with optimized cutting parameters.

2 Results and Discussion

The paralleled microgrooves were machined with the cutting parameters in Table 1, and the surface topographies are shown in Fig. 3, which were observed using a scanning electron microscope (SEM). The burrs were formed by the large plastic deformation and mainly generated on the edge and corner of the workpieces. Although the feature sizes of workpieces machined by micro-milling were very small, the relative sizes of burrs by micro-milling were larger compared the conventional milling. The SEM images in Fig. 2 displayed the difference of burr formation under

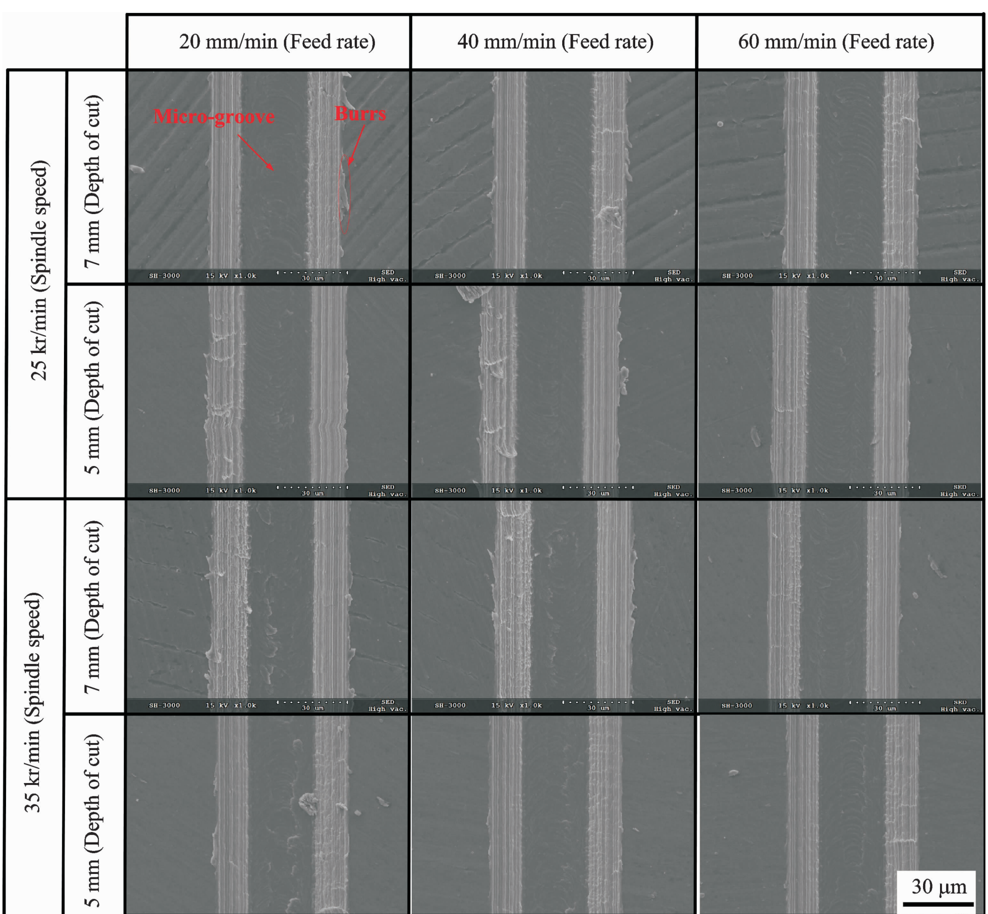

Fig. 3 SEM images of micro-grooves with different cutting parameters

different cutting parameters. For the spindle speed, burrs generated with 25 kr/min were slightly more than that with 35 kr/min, which indicates that spindle speed was not the main influence factor. As presented in SEM images, the dimension of burrs decreased with the decrease of depth of cut. In micro-milling process, the contact area between workpiece and tool should include the extruding region, the friction region and the scratching region. Therefore, the contact area increased with the increase of depth of cut, thus leading to larger burrs formation. For the feed rate, the size of burr shrinked with the increase of feed rate, which was consistent with Ref. [19]. Hence, the least amount of burrs formation was seen for the conditions with the higher spindle speed (35 kr/min), the lower depth of cut (5 μm), and the highest feed rate (60 mm/min), which was an optimized combination of cutting parameters to control burr generation.

After the supporting material being removed, surface topographies of machined workpiece are shown in Fig. 4. The 3D topographies of micro-grooves machined with and without LMPA coating are shown in Fig. 5. It can be seen from Fig. 5(b) that top burrs presented continuous distribution along sides of the micro-grooves. However, there were no obvious burrs on both sides of the micro-grooves machined with LMPA coating, as shown in Fig. 4 and Fig. 5(a), which indicates that LMPA had a significant effect on formation of burrs. The purpose of LMPA coating is to extend the boundaries of the workpiece, which can prevent plastic deformations from deteriorating at the edge of workpiece. When the tool radius slides over the edge of the workpiece, the primary shear zone, the elastic zone and the plastic zone are extended to the LMPA coating, resulting in the burrs generation on support material in place of the workpiece [22].

Pyramid micro-structures on the workpiece surface were built by combining optimized cutting parameters ($S=35$ kr/min, $V_f=60$ mm/min, $a_p=5$ μm) and LMPA coating. The basic dimension was designed based on the cell growing environment, and the pyramids had a square base side of 50 μm and wall inclinations of 60°. The pyramid micro-structures were created by micro-milling in two mutually perpendicular directions sequentially using V-shaped tool with a 60° tip. The machining process is shown in Fig. 6.

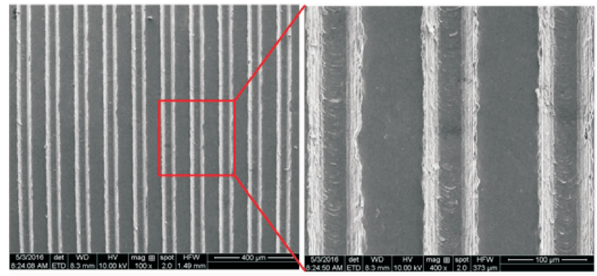

Fig. 4 SEM images of micro-grooves with LMPA

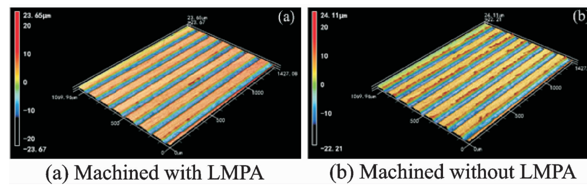

Fig. 5 3D images of micro-grooves

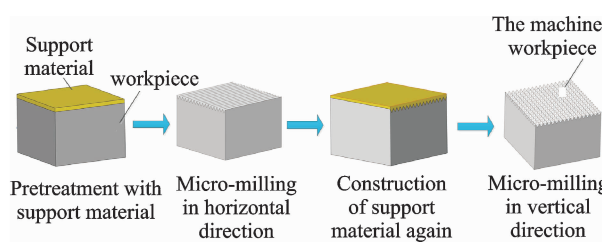

Fig. 6 Machining process of pyramid micro-structure by combining optimized cutting parameters and LMPA coating

According to the optimized schemes, pyramid micro-structures on workpiece surface were built, as shown in Fig. 7. The mutually perpendicular micro-grooves were machined with the depth of 80 μm and groove spacing of 120 μm by

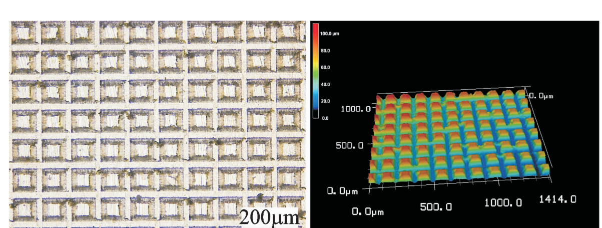

Fig. 7 Optimized surface morphology under laser scanning microscope

micro-milling, which had been confirmed availability to enhance attachment with living tissue[1,23]. In can be seen that slight burrs appeared on the sides of micro-grooves, indicating that the optimized cutting parameters and LMPA coating are effective.

3 Conclusions

(1) In micro-milling process, burrs generated with 25 kr/min were slightly more than that with 35 kr/min. The dimension of burrs decreased with the decrease of depth of cut. In addition, the size of burrs decreased with the increase of feed rate.

(2) LMPA, as supporting material, was used in controlling burrs formation. The results showed that burrs nearly did not appear on both sides of the micro-grooves machined with LMPA coating.

(3) Pyramid micro-structures were built successfully with dimension of 80 μm in depth and 120 μm in groove spacing by micro-milling on the surface of Ti-6Al-4V. A new method for surface modification of implant was introduced by applying micro-milling in the biomedical field.

Acknowledgments

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