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Effects of microstructures on the material removal energy in ultraprecision machining of Ti6Al4V alloys

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Abstract

Material microstructures have significant effects on the mechanical property of the titanium alloy, so the material removal behaviour highly depend on its microstructures. In this paper, effects of equiaxial and martensitic microstructures on material removal behaviour were investigated in the ultraprecision machining of Ti6Al4V alloys from viewpoint of energy consumption. The material removal rate (MRR), material removal energy and specific cutting energy (SCE) were theoretically and experimentally analyzed in the machining. Results show that the MRR of the equiaxial and martensitic alloys is almost same but the material removal energy and SCE of the martensitic alloy are smaller in comparison to the equiaxial alloy. Besides, the effects of MRR and machining parameters on the material removal energy are discussed in machining of the martensitic alloy.

Keywords: Ti6Al4V alloys; material microstructures; material removal; energy consumption; ultraprecision machining;

Introduction

Consumption of mass electrical energy in industrial manufacturing contributes to numerous emission of carbon dioxide because most of the electricity is generated from carbon-rich raw materials[1]. Hence, understanding the energy consumption in the manufacturing is helpful to find feasible solutions to minimize the energy cost. Mechanical machining via a computer numerical control (CNC) lathe is one of the typical methods to manufacture product components. The energy consumed by the material removal is an essential part of the overall demanded energy. It is well known that the yield and fracture strengths of the workpiece vary with the material microstructures, so the required energy to overcome the plastic deformation of the workpiece should be different for different microstructures.

Ti6Al4V alloy has been widely applied in aerospace and medical fields due to its high specific strength, superior thermal stability as well as great biocompatibility[2, 3]. Equiaxial grain and lamellar martensite are two typical microstructures of the Ti6Al4V alloy. The alloy with equiaxial grains generally has a balanced yield strength and ductility, while the alloy with lamellar microstrucutre shows a maxium yield stress but poor ductility[4]. Hence, the different microstructures could result in a variation of material removal deformation due to different mechanical properties in ultraprecison machining (UM) of Ti6Al4V alloys. Most of previous studies focus on investigating the effects of microstructures on the plastic deformation in the machining, but the energy consumption of the material removal was rarely reported in the UM. Furthermore, the cutting parameters of the UM are much smaller in comparison to the conventional machining[5]. The small cutting depth of the UM indicates that less material removal energy is required in the machining, but the time spent is longer than the conventional machining due to the small feedrate, so the total energy consumption of the material removal is still unclear in the UM. Therefore, the purpose of this study is to investigate the energy consumption of the material removal in the UM of the Ti6Al4V alloy with respect to equiaxial and lamellar microstructures.

Materials and experimental procedures

The diameter of the Ti6Al4V workpiece is 3.0±0.02 mm. An ultraprecision machining device (Moore Nanotech 350 FG) was used to conduct the ultraprecision diamond turning experiment using a fresh diamond tool (nose radius: 1.0002 mm, rake angle: 0°, flank clearance angle: 12.5°). The workpiece was roughly turned by another diamond tool to obtain a flat surface, and then finish turning was conducted by the fresh tool with a spindle speed of 1000 rpm, a cutting depth of 3 μm and a feed rate of 4 mm/min. Cutting forces were measured by a Kistler 9256C1 force sensor. The microstructures and surface morphologies were observed by a scanning electron microscope (SEM, Tescan VEGA3) and a three-dimension (3D) surface profiler (Nexview, Zygo).

Energy consumption theory

The net material removal energy E_c is calculated as follows:

$$E_c = F_c L + F_e(\mathrm{R} - r) = F_c \int_0^t v(t)\, dt + F_e(\mathrm{R} - r) \quad (1)$$

where F_c and F_e are the main cutting force and feeding force, respectively. L is the removal length at time t, $v(t)$ is the instant cutting speed, which is expressed by:

$$v(t) = \frac{2\pi\left(R - \frac{f}{60}t\right)n}{60} = v_0 - \frac{\pi f n t}{1800} \quad (2)$$

where f is the feed rate, n is the spindle speed, v_0 is the largest cutting speed at the largest radius. Specific cutting energy (SCE) is an important indicator to evaluate the energy consumption in the machining, and can be estimated as follows:

$$U_c = \frac{E_c}{V} = \frac{E_c}{SL} \quad (3)$$

where Uc and S represent the SCE and material removal area in single one turning pass, respectively.

Results

Fig. 1 shows the equiaxial and martensitic microstructures of the Ti6Al4V alloys. The equiaxial alloy is composed of α phase and β phase or particles, as marked in Fig. 1 (a). The fraction of β particles is calculated to be about 20 % of the total contents based on the ASTM E1245 criteria. The martensitic alloy primarily consists of a considerable amount of orthogonal martensite α′ with lamellar structures, as shown in Fig. 1 (b).

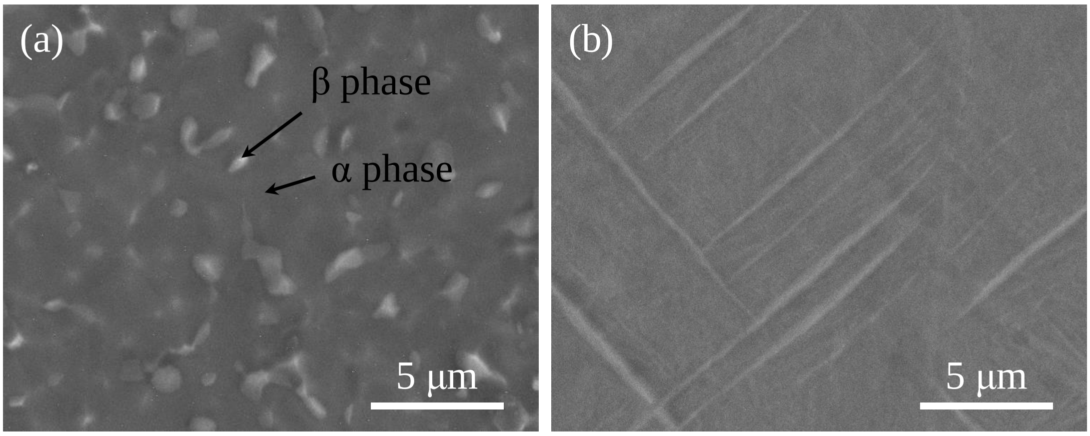

Fig. 1 Ti6Al4V alloy with (a) equiaxial and (b) martensitic microstructures

Fig. 2 shows the evolution of the cutting and feeding forces in machining of the two types of Ti6Al4V alloys. As shown in Fig. 6, even the cutting and feeding forces fluctuate obviously during the machining, the average values of change slightly with the cutting time for both alloys. The average cutting forces are about 0.608 N and 0.395 N, and the average feeding forces are about 0.0234 N and 0.0105 N for the equiaxial and martensitic alloys, respectively. The forces for the alloy with equiaxial microstructure are larger than that with martensitic microstructures, which indicates that more power is required to remove the equiaxial alloy.

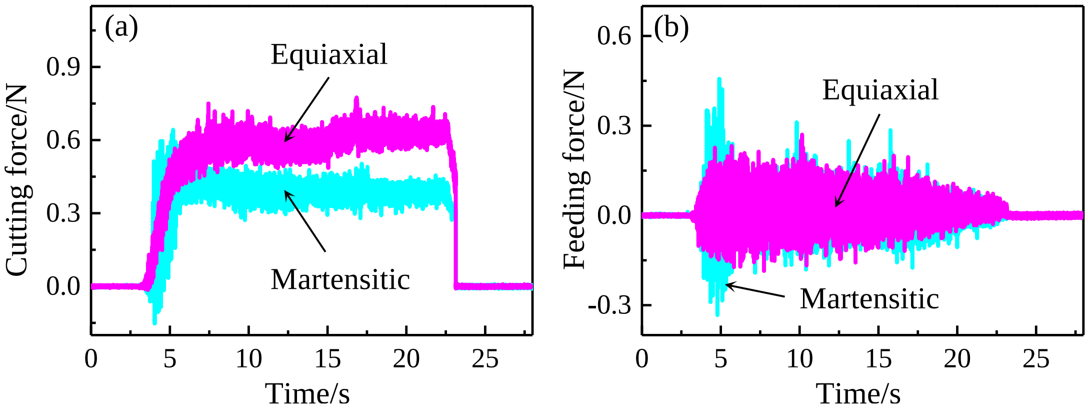

Fig. 2 Evolution of the (a) cutting forces and (b) feeding forces during machining of the equiaxial and martensitic Ti6Al4V alloys

The material removal rate (MRR) is one of important indicators to evaluate the cutting efficiency in the machining, which is a ratio between material removal volume and cutting time. Since the cutting radius gradually reduces with the cutting time, the MRR can also be expressed by a relationship between MRR and cutting radius, as shown in Fig. 3 (a). It is seen that the MRR drops linearly with the reduction of the turning radius due to the decreasing of the cutting speeds for both of the equiaxial and martensitic alloys, but the MRR of the two types of alloys shows almost same at the same radius.

Fig. 3 (b) illustrates the evolution of the material removal energy with the cutting radius, The energy evolution of the two types of alloy shows a similar trend with that of the martensitic alloy, i.e. the energy increases rapidly at the initial stage and reduces gradually with the decreasing of the turning radius. The required energy of the equiaxial alloy is consistently higher than that of the martensitic alloy in the whole single one turning pass, and the gap between them increases with the radius. Consequently, the total energies demanded to finish single one turning pass are about 1.075 J and 0.698 J for the equiaxial and martensitic alloy, respectively. Hence, the equiaxial titanium workpiece requires more energy to overcome material deformation.

The relationships of between material removal energy, SCE and MRR in single one turning pass are shown in Fig. 3 (c) and (d). Both energy and SCE in the material removal stage of the UPDT reduce with the increasing of the MRR for the two types of Ti6Al4V alloys, which indicates that energy consumption could be reduced by enhancing the MRR. Furthermore, the values of SCE could reach about 9.21492 J/mm^3 and 6.01547 J/mm^3 for the equiaxial and martensitic alloys, respectively. Though the required energy of single one pass turning and MRR of the UPDT is much lower than the conventional machining, the SCE of

UPDT is higher than that of the conventional machining of the titanium alloy with values ranging from about 2 to 5 J/mm^3 [6, 7].

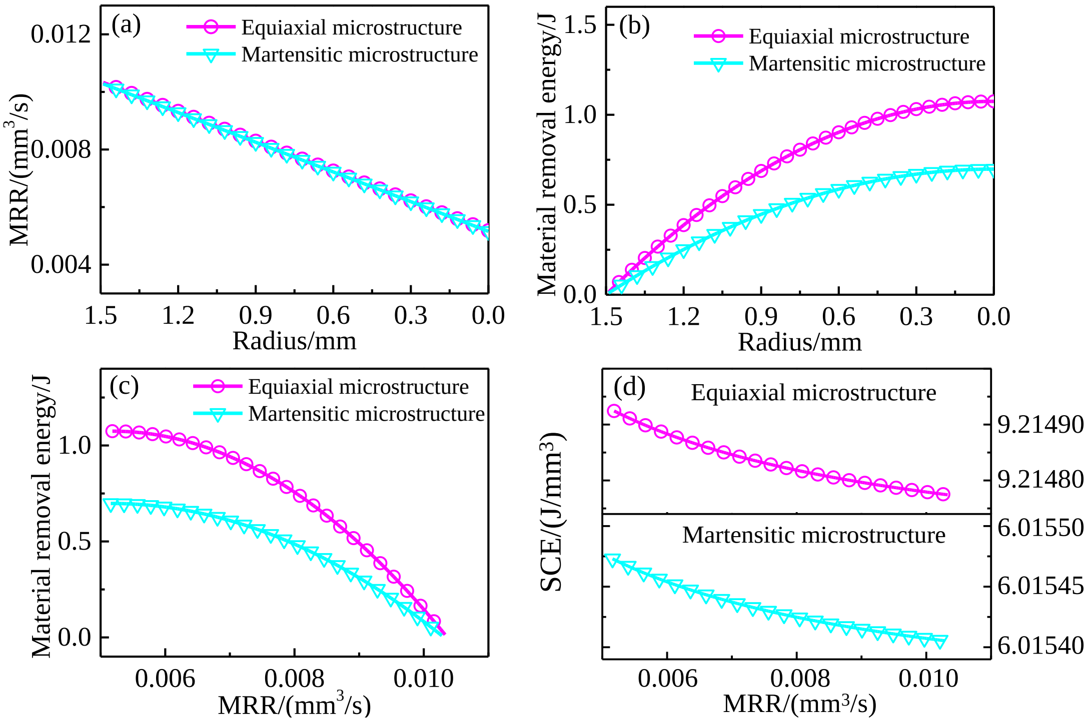

Fig. 3 Evolution of (a) MRR and (b) material removal energy with cutting radius; Evolution of (c) material removal energy and (d) SCE with the MRR.

Since the energy consumption reduces with the MRR, it is necessary to explore how to increase the MRR. Fig. 4 shows the effects of depth of cuts and feed rates on the MRR in the UM of Ti6Al4V alloys with martensitic microstructures at spindle speeds of 500 rpm, 1000 rpm, 2000 rpm and 3000 rpm, respectively. For a given spindle speed, the MRR increases with the depth of cut and feed rates. For example, the MRR in this experimental condition is about 0.005157 mm^3/s, which is marked by a white point shown in Fig. 4 (b). If the depth of cut and feed increased twice to 6 μm and 8 mm/min respectively, the MRR could reach about 0.01526 mm^3/s, achieving nearly three times increment of MRR. However, the contribution of the depth of cut to the MRR in the UPDT is significant in comparison to that of the feed rate. This means that an increase in the depth of cut could obviously promote the MRR , while an increase in the feed rate contributes slightly to the MRR promotion. Besides, an increase in the spindle speed also results in a high MRR. When the spindle speed increases from 1000 rpm to 3000 rpm at the same depth of cut and feed rate with this experiment, the MRR rise from about 0.005157 mm^3/s to about 0.01430 mm^3/s. Therefore, increasing of cutting depth and spindle speed benefits for energy saving.

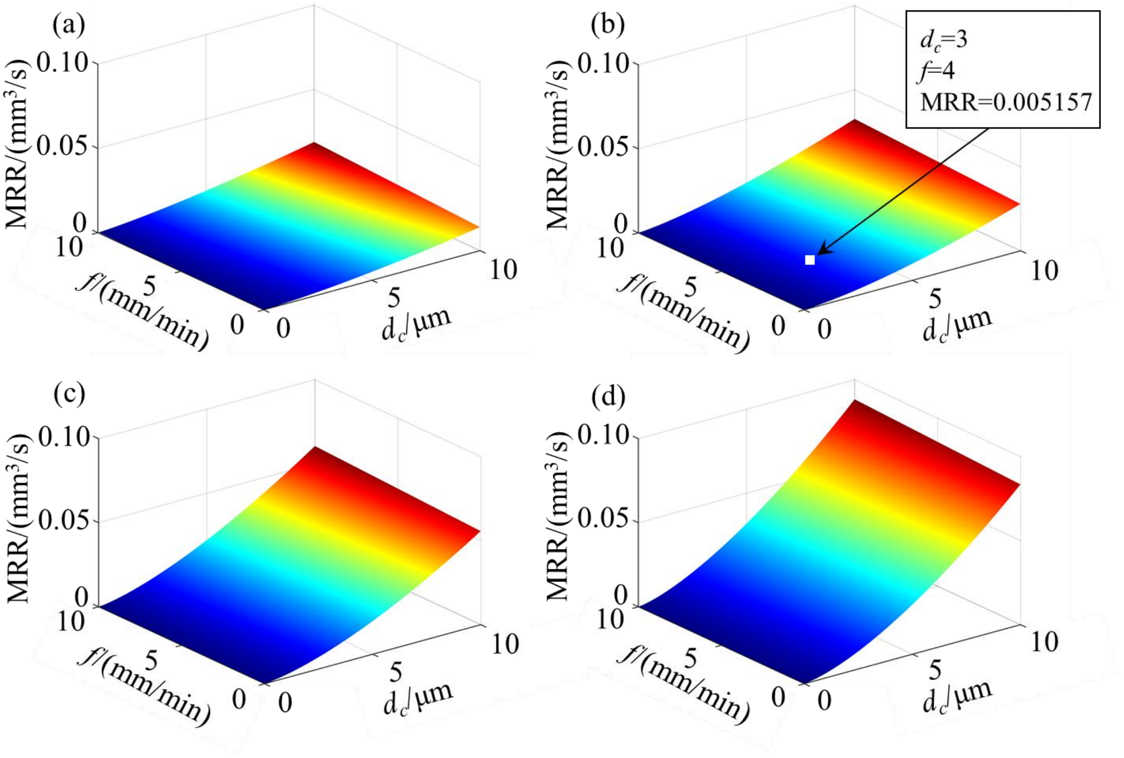

Fig. 4 Relationships among the MRR, depths of cut and feed rates at the spindle speeds of (a) 500 rpm, (b) 1000 rpm, (c) 2000 rpm and (d) 3000 rpm

Conclusion

The main conclusion of this study is drawn as follows:

(1) The energy cost by the material removal of the Ti6Al4V alloy with equiaxial microstructure is higher than that of the alloy with martensitic microstructure in UM.

(2) Even the energy consumption and MRR of the UM is much smaller than the conventional machining, the SCE of the UM is at the same level as the conventional machining of titanium alloys.

(3) The net material removal energy is closed correlated to the depth of cut and spindle speed but is not affected by the feedrate.

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