Mechanical property and machinability study on polyetheretherketone

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Polyetheretherketone (PEEK) is a high performance composite with distinctive properties and characteristics. It has greater strength and rigidity than many other traditional engineering composites. The PEEK has been integrated into the special applications in various fields of structural components, so it is necessary to study the mechanical property and machinability to further enhance the application range, especially in ultra-precision manufacturing. This paper aims to investigate the mechanical property and machinability of the unfilled PEEK. The nano-indentation experiment is adopted to study the microscope mechanical property, and the nano-indentation hardness and elastic modulus of PEEK are analyzed. The single point diamond turning (SPDT) is used to machine the PEEK. Form accuracy and surface roughness of the machined surface reach submicron degree in PV and nanometer order in Ra respectively. The results show that the PEEK has good mechanical property and machinability.

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Keywords: Polyetheretherketone (PEEK), Mechanical property, Nano-indentation, Machinability, Single point diamond turning (SPDT)

1. Introduction

Polyetheretherketone (PEEK) is an organic polymer thermoplastic material with high specific strength and stiffness, wear resistance, dimensional stability, good corrosive resistance, low weight and physical and mechanical directional properties [1-3]. These inherent properties enable it to be used in a wide range of applications, such as automotive, aerospace and medical segment, and many conventional metal materials has be replaced by this material [4].

The increasing demand is limited by the machining technology for PEEK. Since the PEEK structural components are generally manufactured by extrusion, for which the machined components need additional machining operations to obtain the surface with higher quality [2]. So, the researches on effective manufacturing technology for PEEK with micro-structured surfaces are very necessary. For the current ultra-precision machining methods, single point diamond turning (SPDT) has become an outstanding machining process to produce high precision surfaces in one-stage process without subsequent processing [5-7]. But the materials currently used in SPDT are mainly non-ferrous metals.

Presently, several papers about PEEK are concentrated on macroscopic mechanical properties [8, 9] and crystallization behavor [10-12]. Few papers discussed the relation between microscope mechanical properties and machinability for PEEK during ultra-precision manufacturing.

In order to better analyze and use the good properties of PEEK materials, the microscope mechanical properties of PEEK are investigated by nano-indentation experiment in this paper. The nano-indentation hardness, elastic modulus and load-displacement are analyzed, respectively. Then, the SPDT experiment is conducted on the PEEK surface to study the machinability.

2. Nano-indentation experiments and results analysis

To conduct the nano-indentation experiments, several cylindrical PEEK samples are prepared with R=10mm and L=10mm. Before the test, the end surface of the workpiece has been polished. The sample can be observed in Fig. 1.

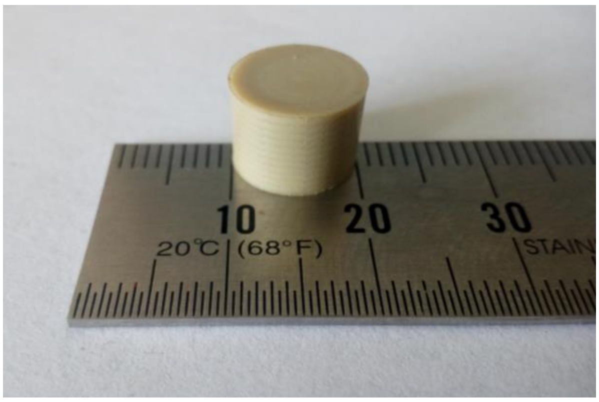


Fig. 1. The used PEEK sample.

The microscope mechanical property is studied in nano-scale and the experiment is conducted in nano-indentation apparatus Agilent Nano Indenter G200. The profile of adopted indenter is a triangular pyramid head with 120° apex angle. To study the change rule of nano-indentation hardness and elastic modulus with different indentation depth, five groups of experiments are planned, and the designed indentation depths are 1μm, 2μm, 4μm, 6μm, 8μm respectively. Four points are tested in every group with the same indentation depth to ensure the validity of the experiment dates. Fig. 2 gives the micro-photograph of indentation for PEEK.

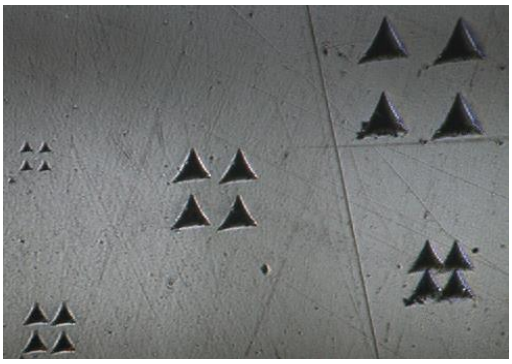


Fig. 2. The micro-photograph of indentation for PEEK.

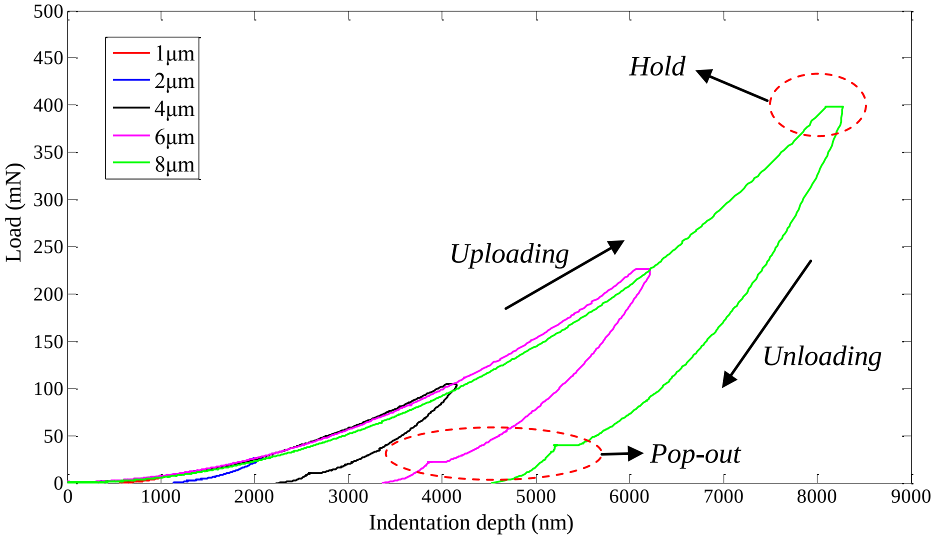


Fig. 3. The relation curve between load and displacement for PEEK.

To research the microscope mechanical property of PEEK, the date of load and displacement of indenter are continuously recorded in the process of uploading and unloading. After the nose of the triangular pyramid head just touched the end surface of the workpiece, then in the following intending, the displacement of indenter is same as the indentation depth in PEEK material surface. Fig. 3 presents the relation curve of load-displacement under the condition of different maximum pre-setting indentation depths.

As shown in Fig. 3, five groups of load-displacement curve have the same changing trends. The process of uploading curve is normal which conform to general rule. In the maximum pressure holding process, in the first period of holding process, the indentation depth is increasing with the increasement of holding time, then the indentation depth was not changed. During the unloading phase, the pop-out phenomena appear in all curves, which mainly attribute to creep of the material or the phase transition of PEEK in the indenter function area [13, 14]. To this problem, there are several different explains [14]. It can be seen that the critical maximum load that the pop-out appeared for PEEK is in the range of 0~50mN, and the corresponding load value that the pop-out phenomenon appeared has the increasing trend with the increase the maximum depth.

Nano-indentation hardness and elastic modulus are two main parameters of microscope mechanical property for PEEK. Set the peak hold time 2*s*, the obtained nano-indentation hardness and elastic modulus of every indentation point are listed in Table 1 and Table 2, respectively.

Table 1. Nano-indentation hardness value of every indentation point (GPa).

Designed depth	Hardness				Mean hardness	Mean actual depth
	Point 1	Point 2	Point 3	Point 4		
1μm	0.354	0.366	0.383	0.355	0.365	1.017μm
2μm	0.339	0. 359	0.353	0.347	0.350	2.061μm
4μm	0.345	0.340	0.342	0.350	0.345	4.129μm
6μm	0.338	0.328	0.340	0.331	0.334	6.206μm
8μm	0.327	0.324	0.329	0.327	0.327	8.257μm

Table 2. Elastic modulus value of every indentation point (GPa).

Designed depth	Modulus				Mean modulus	Mean actual depth
	Point 1	Point 2	Point 3	Point 4		
1μm	5.553	5.152	5.067	5.211	5.246	1.017μm
2μm	5.534	5.024	5.318	5.340	5.304	2.061μm
4μm	5.097	4.994	5.269	5.156	5.129	4.129μm
6μm	5.058	4.888	4.993	4.848	4.947	6.206μm
8μm	5.173	5.085	5.256	5.238	5.188	8.257μm

As shown in Table 1 and Table 2, although the indentation depths are designed from 1μm to 8μm, the nose of the triangular pyramid head couldn't move to the desired indentation depth accurately due to displacement error in its direction of motion. For four points of the same indentation depth, the nano-indentation hardness and elastic modulus are remained stable relatively, which indicates that the microscope mechanical property for PEEK is uniform. For five groups of indentation depth, the nano-indentation hardness and elastic modulus are both variable under different impression depths.

The change in the relationship between nano-indentation hardness and indentation depth is displayed in Fig. 4. It demonstrates that the nano-indentation hardness of PEEK is decreased with the increasing of indentation depth, while is not a constant. This phenomenon may be caused by the scale effect, which is common and inevitable when the engineering plastics under a certain load. The size effect has been studied by many researchers, and there are several explanations on the indentation size effect [15-17]. One typical explanation is that the geometrically necessary dislocations in indentation process could increase the effective yield stress of material and the dislocation density increases with the decrease of indentation depth, which resulting in the indentation size effect [15]. So, it is reasonable that the nano-indentation hardness of PEEK is decreased with the increase of indentation depth while indentation experiment.

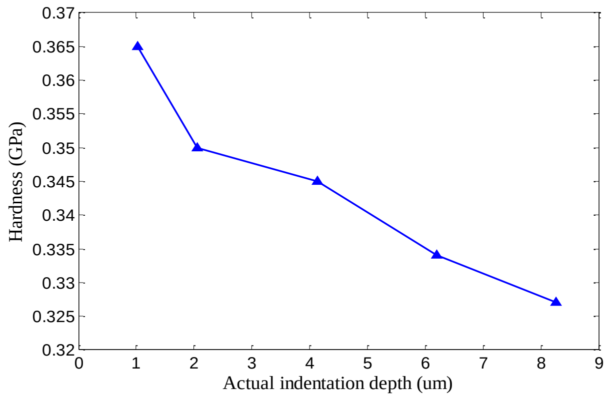


Fig. 4. The relationship between nano-indentation hardness and indentation depth.

The relationship between elastic modulus and indentation depth is illustrated in Fig. 5. The measured elastic modulus shows irregular variation during the increasing of indentation depth, as shown in Fig. 5, which is mainly due to the discontinuity of used PEEK material.

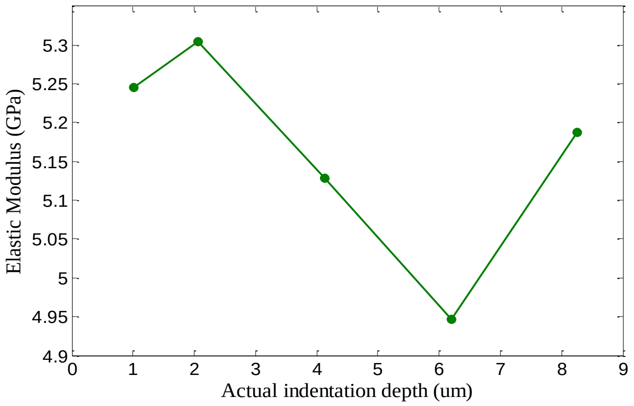


Fig. 5. The relationship between elastic modulus and indentation depth.

3. Turning experiments and results analysis

To broaden the application of PEEK in special high-precision field, it is important to study the machinability of PEEK, and the higher surface quality is the aim of the research. SPDT is an outstanding ultra-precision machining technology and it is more suitable to cut the non-ferrous metals, such as aluminum and copper. Since the PEEK is a type of thermoplastic plastic, producing a high quality PEEK surface with SPDT is a challenge work. Fig. 6 gives the main section of the SPDT setup.

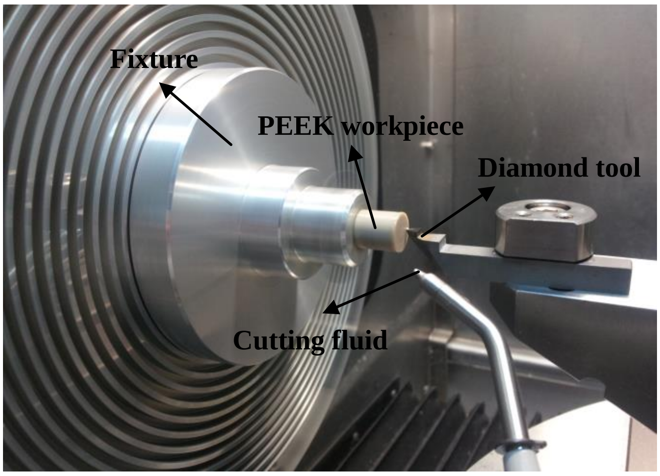
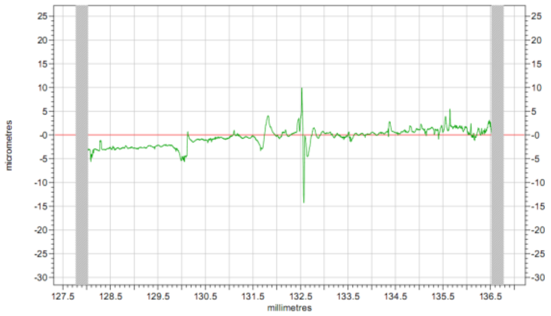


Fig. 6. The main section of the SPDT setup.

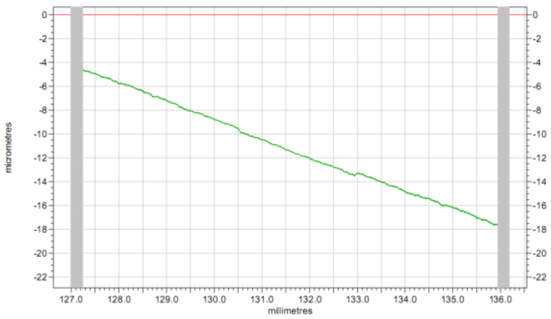
The turning experiment is conducted in ultra-precision lathe NANOFORM 250, and a sample flat surface is prepared prior to the machining. The surface can be machined using the lathe with X-axis and Z-axis. In view of the characteristic of PEEK material, the key machining parameters are selected as F=1.0mm/min, S=1500rpm. A single-crystal diamond cutting tool is used and parameters of the tool are 0.5mm radius, 0° rake angle and 10° clearance angle.

To verify the feasibility of ultra-precision manufacturing for PEEK, the form accuracy and surface roughness of the machined surface are measured by TAYLOR HOBSON. The machined PEEK surface and schematic diagram of measurement are displayed in Fig. 7, and the profiles of surface before and after turning are indicated in Fig. 8 (a) and Fig. 8 (b), respectively. It can be seen that the PV value has significantly decreased. The smoothness of machined surface has improved obviously compared to the surface before turning.

Fig. 7. The schematic diagram of measurement.



(a)

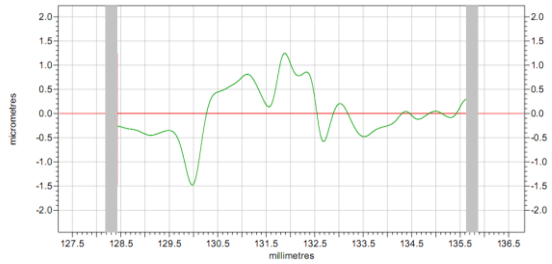


(b)

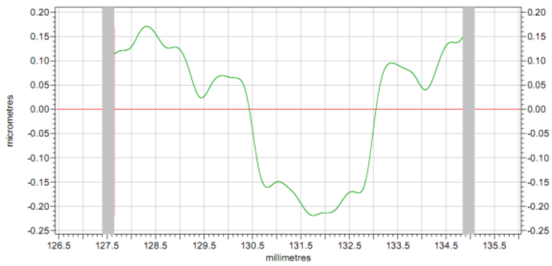
Fig. 8. The surface profiles (a) surface before turning (b) surface after turning.

The corresponding form accuracy and surface roughness for surface before and after turning are analyzed in Fig. 9 and Fig. 10, respectively. Fig. 9 is the modified profile for the raw profile, and the value between peak and valley is used to evaluate the form accuracy. As indicated in Fig.9 (a), the form accuracy of surface before turning is 2.7μm, and dropped to 0.39μm after turning in Fig. 9 (b). For the surface roughness, the value of Ra is 0.149μm for pre-turning surface, but it downed to 0.014μm after SPDT, as presented in Fig. 10.

J. Paulo Davim and Pedro Reis [2] found that the range of Ra for PEEK can be 0.6~3μm and for glass fiber reinforced PEEK can be 0.7~3.39μm while cutting with the PCD tools. F. Mata [18] concluded that it is possible to obtain surface with 1.45~4.01μm of Ra for glass fiber reinforced PEEK using K15 tools. Compared with the results of Ra in previous literatures, it can be seen that the surface machined with SPDT has better surface quality. Thus, the PEEK materials have better machinability while machining with the SPDT.

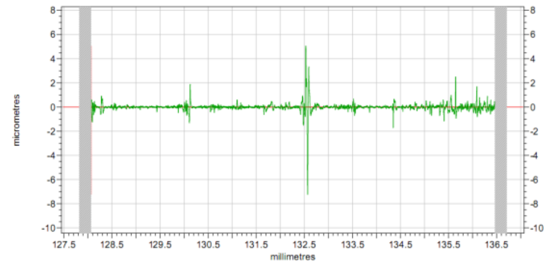


(a)

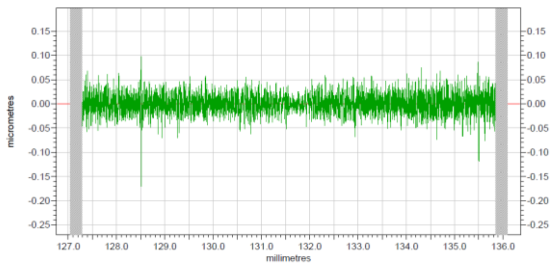


(b)

Fig. 9. The form accuracy (a) surface before turning (b) surface after turning.



(a)



(b)

Fig. 10. The surface roughness (a) surface before turning (b) surface after turning.

4. Conclusion

The study concentrated on microscope mechanical property and machinability for the new engineering plastic PEEK. The microscope mechanical property is analyzed by nano-indentation experiment, and the results of nano-indentation hardness, elastic modulus and load-displacement curve demonstrate that the PEEK posses superior microscope mechanical property. Besides, a flat surface is machined with SPDT technology for PEEK. The machinability of PEEK is researched by comparing the form accuracy and surface roughness of machined surface with pre-machined surface. The surface with 0.39μm form accuracy in PV and 0.014μm surface roughness in Ra can be obtained, which illustrate that the PEEK owns better machinability.

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