

**RESEARCH ON CUTTING PERFORMANCE OF CERAMIC
CUTTING TOOLS IN MILLING HIGH DENSITY
FIBERBOARD**

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ABSTRACT

The effect of cutting parameters and tool parameters on cutting forces and tool wear were investigated in high density fiberboard (HDF) peripheral up-milling using toughened ceramic cutting tools. The results showed that whether at low speed cutting or high speed cutting, the tangential forces F_t and normal forces F_r increased slowly with the increase of cutting length. The tangential forces F_t and normal forces F_r at low speed cutting were higher than that at high speed cutting. The tangential forces F_t and normal forces F_r decreased with the decrease of wedge angle in the same rake angle. Then, the effect of high cutting speed on the flank wear was greater than that at low cutting speed. The bigger wedge angle tools led to the serious flank wear. The main wear pattern in milling HDF consisted of pull-out of the grain, flaking, chipping and cracking, the main wear mechanism were adhesive and abrasive wear.

KEYWORDS: Ceramic cutting tool, high density fiberboard, cutting forces, tool wear.

INTRODUCTION

High density fiberboard (HDF) is a wood-composites formed by break down softwood and

hardwood into wood fiber, in a defibrator, combining it with wax and resin, and forming panels by applying high temperature and pressure in a hot press (Ayrilmis et al. 2007). Since 1999, China has become the largest country in the production of fiberboard, and high density fiberboard with its fine texture, stable performance, strong grip nails, well resistance to deformation, surface decoration, is more and more popular used in the world, which has been widely used in construction and building industries.

With broadening application of HDF, it has been applied in door, windows, furniture, and other complicated profiled product, most secondary processing methods such as milling, planning, routing and sanding, have been conducted. Especially, peripheral milling, which is a process consisting of a rotary cutting motion and a linear feeding motion, is the most common machining operation, a material removal process, which can create a variety of features on a part by cutting away the unwanted material (Guo et al. 2015).

As mentioned above, due to the mass production of high density fiberboard, it has given great challenges to the wood processing industries. At present, the most frequently used wood cutting tool material is cemented carbide. Even though cemented carbide cutting tools can provide a good ration of hardness and fracture toughness (Guo et al. 2014a, b), but it can't meet the modern wood processing industry. As we all know, the wood cutting processing is very complicated as cutting speed are higher 5 times than conventional metal cutting speed (Sommer et al. 2013a, b). Wooden products are anisotropic and inhomogeneous contain knots and silicates. Besides, the tannins and abrasive in the wooden products also shorten the lifetime of cutting tools (Darmawan et al. 2011), leading to the low efficiency of industrial production. In order to improve the efficiency, monocrystalline diamond tools with highest hardness of more than 10000 HV are used in wood processing. Because of the expensive cost, it can't be used widely (Sommer et al. 2013a, b). Those all make our eyes turn to ceramic cutting tools spontaneously.

Due to the fracture toughness of ceramic, it limited the application in wood processing. However, with the development of toughening technology (Gogolewski et al. 2009), ceramics has become promising material as it exhibit high hardness, excellent wear resistance and no sensitivity to chemical attack (Smirnov et al. 2011, Sommer et al. 2012). Moreover, the low density may offer benefits in high speed cutting, where centrifugal forces due to high spindle rotation occur

(Sommer et al. 2013a, b). Last, it has low friction coefficient, which is more conducive to high-speed wood processing (Guo et al. 2013). All in all, comparing with cemented carbide and diamond cutting tools, ceramic cutting tools has the advantage that they can't go beyond. Gogolewski et al. (2009) was the first person to study the alumina based ceramic cutting tools for machining, his research showed that the main wear was chipping, but when grain sizes were reduced, the main wear became abrasive wear. A feasibility research carried out by Eblagon et al. (2007), their results showed ceramic cutting tools have superior lifetime compared with cemented carbide cutting tools. Then, Streher et al. (2012) measured the edge recession after the lifetime cutting test, they found the recession of the Si₃N₄/SiC cutting tools is less than one half of the minimum edge recession of the cemented carbide cutting tools. Streher et al. (20012) found that Si₃N₄ -based ceramic matrix composites have the potential to be used for industrial wood-cutting insert by a series of experiments. In fact, there are few studies about ceramic cutting tools used in wood processing compared with the studies on ceramic cutting tools used in metal processing (Tian et al. 2013) which results in many puzzling problems, such as how to improve the cutting performance, design the reasonable tool parameters and cutting parameter.

In order to provide theoretical basis of ceramic cutting tools used in wood processing, this paper took an experimental study on cutting performance of different structural parameters ceramic cutting tools at different cutting speed in milling HDF. The effect of cutting speed, cutting length, and tool parameter on cutting forces and tool wear were investigated and discussed.

MATERIAL AND METHODS

Material

Workpiece materials

The HDF was used as the tested samples in this experiment which was supplied by Shengxiang group Co.Ltd.in China. The dimension of the tested HDF samples was $150 \times 80 \times 10.7$ mm ($L \times W \times T$). The physical and mechanical properties of HDF are described in Tab. 1.

Tab.1: Physical and mechanical properties of HDF.

Sample	Density ($\text{kg}\cdot\text{m}^{-3}$)	MOE (MPa)	MOR (MPa)
HDF	861	4312	49.7

Cutting tools

In this experiment, Al_2O_3 ceramic cutting tools, made by Kyocera Trading Co.Ltd.in China, were used in these milling tests, which were toughened by TiC. The cutter is capable of carrying six inserts with a diameter of 100 mm. In each test, six inserts were mounted on the cutter to maintain constant cutting condition. Then, the structure parameter and mechanical properties of ceramic cutting tools are given in Fig.1 and Tab. 2.

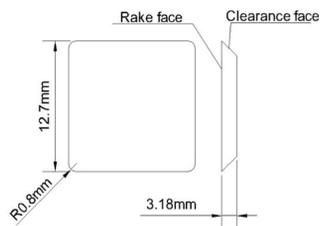


Fig.1: The structure parameter of ceramic cutting tools.

Tab.2: The structure parameter and mechanical properties of tools.

Ceramic cutting tools	Structure parameter			Mechanical properties			
	Rake angle ($^\circ$)	Wedge angle ($^\circ$)	Flank angle ($^\circ$)	Chemical composition	Hardness/ (GPa)	Flexural strength (MPa)	Toughness (MPa)
Tool A	6	79	5	$\text{Al}_2\text{O}_3+\text{TiC}$	20.1	980	4.1
Tool B	6	75	9				
Tool C	6	70	14				

Methods

Experiment set up

Up-milling was adopted for the test of cutting forces and tool wear, which were performed on a CNC machine (MGk01A, Nanxing group Co. Ltd, China). In the process of milling experiment, the dynamic cutting forces F_x , F_y and F_z were measured using a quartz three-component dynamometer (Kistler 9257B, Switzerland). As shown in Fig. 2, during milling, HDF samples were fastened to dynamometer, which fixed to the worktable. A charge amplify was used to amplify and condition input date, then the computer can get the date of the dynamic cutting forces. The cutting force were measured according to F_x , F_y and F_z directions, F_x was

defined as the cutting force component parallel to feed direction, F_y was defined as the cutting force component perpendicular to feed direction. F_z was defined as the cutting force component parallel to axial direction, due to the ceramic cutting tools with straight cutting edges, the axial cutting forces F_z are almost zero and will not be consider as specialized problems. At each test, cutting forces were measured three times and a mean value was reported. After the end of milling experiment, the microstructure of ceramic cutting tools were observed by SEM and the wear mechanism of ceramic cutting tools were analyzed by energy dispersive spectroscopy EDS, that all revealed the performance of ceramic cutting tools in milling HDF.

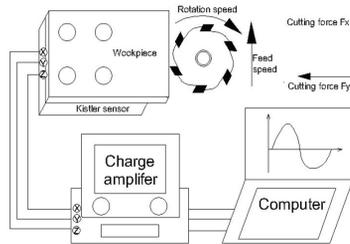


Fig.2: The schematic diagram of cutting forces measuring system.

Experimental design

The experiments were performed with three structure parameters tools, showed in Tab. 2, at two different cutting speed, showed in Tab. 3. For the better analysis, this paper selected two different feed and spindle speed, but in the same cutting depth and the average chip thickness in the whole experiment. It is worth mention that the average chip thickness was attained by combination of low rotation and feed speed in low speed cutting condition and high rotation and feed speed in high speed cutting condition. Tab. 3 shows how the average chip thickness could be obtained in different ways where the number of teeth (z) was 6, the depth of cut (h) was 1 mm and the cutting diameter (D) was 100 mm. All in all, there are two groups of cutting condition: low speed cutting condition and high speed condition, which could reach the same average chip thickness in this set up. The aim of such experiment design was to investigate the effect of cutting speed, cutting length and structure parameter on cutting forces and tool wear in the same average chip thickness.

The average chip thickness calculating Eq. 1 based on the Eq. given by Koch (1964):

$$a_{av} = \frac{U}{n \cdot z} \sqrt{\frac{h}{D}} \quad (\text{mm}) \quad (1)$$

where: a_{av} - average chip thickness (mm), that can calculate from Eq. 1,
 U - feed rate ($\text{mm} \cdot \text{min}^{-1}$),
 n - rotation speed (rpm),
 z - number of teeth on tool,
 h - cutting depth (mm),
 D - diameter of tool (mm).

Tab. 3: The design of the same average chip thickness value can be reached either by changing the feed rate at low rotation speed or by changing the feed rate at high rotation speed.

Test number	n (r·min ⁻¹)	U (mm·min ⁻¹)	aav (mm)	Tools	h (mm)	Cutting length (m)	Cutting condition
1	5000	30000	0.1	A/B/C	1	0	Low speed cutting
2	5000	30000	0.1	A/B/C	1	5	Low speed cutting
3	5000	30000	0.1	A/B/C	1	10	Low speed cutting
4	5000	30000	0.1	A/B/C	1	15	Low speed cutting
5	5000	30000	0.1	A/B/C	1	20	Low speed cutting
6	5000	30000	0.1	A/B/C	1	25	Low speed cutting
7	10000	60000	0.1	A/B/C	1	0	High speed cutting
8	10000	60000	0.1	A/B/C	1	5	High speed cutting
9	10000	60000	0.1	A/B/C	1	10	High speed cutting
10	10000	60000	0.1	A/B/C	1	15	High speed cutting
11	10000	60000	0.1	A/B/C	1	20	High speed cutting
12	10000	60000	0.1	A/B/C	1	25	High speed cutting

RESULTS AND DISCUSSION

Mathematical model and analysis of cutting forces

As above, F_x was defined as the cutting force component parallel to feed direction, F_y was defined as the cutting force component perpendicular to feed direction, which all got from the date of the dynamic cutting forces in computer. θ ($^\circ$) was defined as the angle between the direction of rotation and the direction of feed. In order to study the cutting force better preferably, the tangential forces F_t and the normal forces F_r were used as reference values, which represented the cutting forces component perpendicular to the radius direction and parallel to the radius direction respectively. Then, it can be obtained by conversion Eqs. 2 and 3.

The angle between the direction of rotation and the direction of feed calculating Eq. 2 and cutting forces conversion Eq. 3:

$$\Theta = \arcsin \sqrt{\frac{h}{D}} \quad (2)$$

$$\begin{pmatrix} F_t \\ F_r \end{pmatrix} = \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} F_x \\ F_y \end{pmatrix} \quad (3)$$

where: $h=1$ mm, $D=100$ mm, $\sin \theta=0.1$ and $\cos \theta=0.995$, then the cutting forces F_t and F_r can be calculated according to the Eqs. 2 and 3.

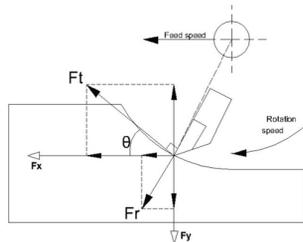


Fig. 3: The schematic diagram of cutting forces.

Fig. 4 shows the signal graph of transformed cutting forces, the conclusion can be got that the milling was a discontinuous process. Each cutting edge started from the moment of cutting the workpiece and end to the moment of leaving the work piece, at the same time, the cutting forces increased from zero to the maximum, then decreased from maximum to zero, which was defined as a milling cycle. In each milling cycle, the change of the tangential forces F_t was bigger than the normal forces F_r . In cutting processing, the tangential forces F_t came from the rake face that removed the chips connected with machined surface, the clearance face that overcame the friction between and machined surface, and the cutting edge that destroyed the HDF. The normal forces F_r came from the extrusion that originated in the elastic deformation of workpiece. Besides, some jagged peaks exist in picture, it was due to the vibration of engine bed and some hard particles exist in HDF, which affect the dynamic cutting forces.

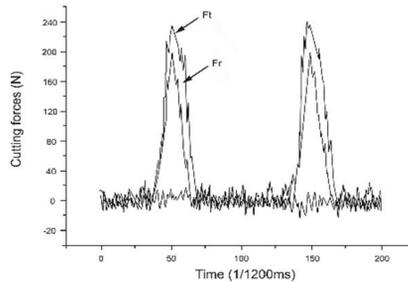


Fig. 4: The signal graph of transformed cutting forces (tool C at low speed cutting).

Influential factors analysis of the cutting forces

Cutting forces, which are importance basis for tool design, are affected by many factors, such as workpiece material, cutting speed, cutting thickness, friction, cutting length, tool parameter, etc. (Guo et al. 2014). Hernandez et al. (2014) studied the effects of rake angle, cutting direction, and cutting depth on cutting forces, which showed that as rake angle increased, cutting forces decreased. Džinčić and Skakić (2012) showed with regard to intensity, cutting depth has a greater effect on the cutting force; If the cutting depth increases, the increase of cutting force was faster when feed per edge was greater. If the feed per edge was increased, the increase of tangential cutting force was more significant when the value of cutting depth was greater. In this paper, the effects of cutting length, cutting speed and tool parameter on the cutting forces are researched.

The influence of cutting length on cutting forces

As shown in Fig. 5, under the same average chip thickness condition, whether at low cutting speed cutting or at high speed cutting, the tangential forces F_t and the normal forces F_r increased slowly with the increase of cutting length. Because tool wear became the main reason for the increase of cutting forces. With the increase of cutting length, the cutting edge became wear increasing gradually, even appeared breakage, which led to the increase of resistance in separating chips from workpiece. The flank wear increased, which results in the more serious friction between the flank and the machined surface. For these two reasons were the cutting forces increased with increase of cutting length.

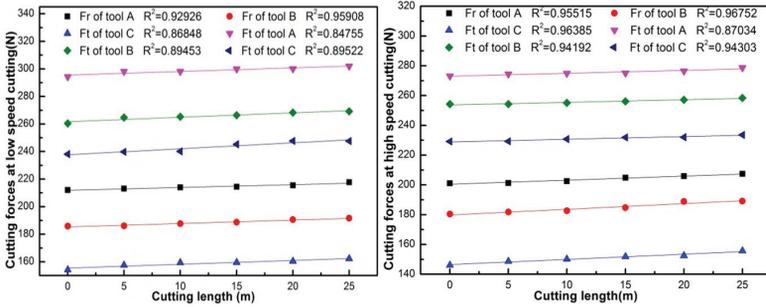


Fig. 5: The influence of cutting length on cutting forces.

The influence of cutting speed on cutting forces

As shown in Fig. 6, the influence of cutting speed on the cutting forces is relatively obvious, which reveals the tangential forces F_t and the normal forces F_r at low speed cutting are higher than that at high speed cutting. The result accords with the experimental conclusion of the classical alonmen experiment. Because in unit time, with the increase of cutting speed, the friction frequency between tool and workpiece was increased, then the temperature of contact zone was increased and led to the lower friction coefficient, what's more, with the increase of cutting speed, the deformation coefficient of chips became lower. Finally, the tangential forces F_t and normal forces F_r at low speed cutting were higher than that at high speed cutting.

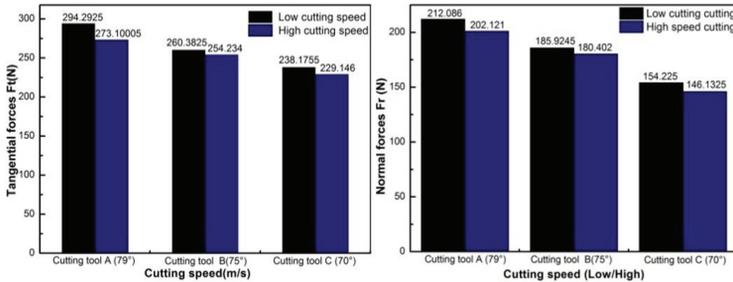


Fig. 6: The influence of cutting speed on cutting forces.

The influence of tool parameter on cutting forces

The influence of tool parameter on cutting forces is shown in Fig. 7, which reveals whether at high cutting speed cutting or in low cutting speed, the tangential forces F_t and normal forces F_r decreased with the decrease of wedge angle at the same rake angle. The reasons are as follow, in the same rake angle, the sharper cutting tool was more easily to split the glue between the fibers. Then with the increase of clearance angle, the friction between flank and machined surface was decreased, which all led to the decrease of cutting forces.

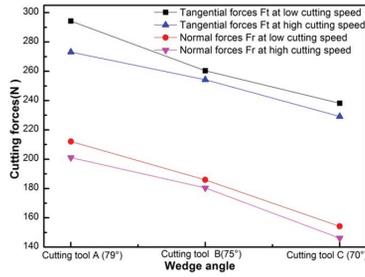


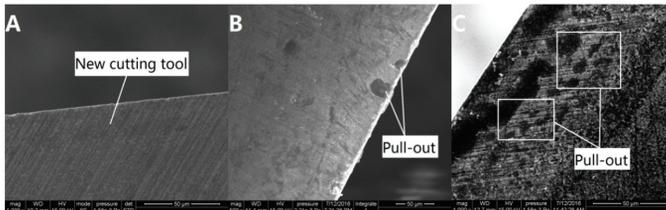
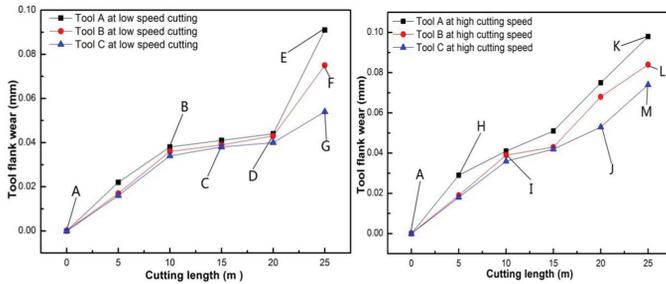
Fig. 7. The influence of tool parameter on cutting forces.

Influential factors analysis of the tool wear

Tool wear is a complex process, which is caused by the comprehensive effect of chemical, mechanical and thermal. Along with the cutting process, the cutting edge is gradually worn away from sharp edge, which led to the increase of cutting forces, the decrease of cutting quality, and the increase of cutting temperature (Guo et al. 2016). In this paper, the effect of cutting length, cutting speed and tool parameter on tool wear was investigated and discussed.

The influence of cutting length on tool flank wear

Fig. 8 shows the influence of cutting length on tool flank wear, which reveals the tool flank wear increases with the increase of the cutting length. Because with the increase of cutting length, the cutting edge became wear increasing gradually, the friction between the tool and the workpiece increased, and cutting temperature increased too. In addition, in the cutting process, cutting tools inevitably encountered some hard particles, which all had a great influence on tool wear. It can be seen from the figure that the tool appeared wear in different degree, it included pull-out of the grain, flaking, chipping and cracking.



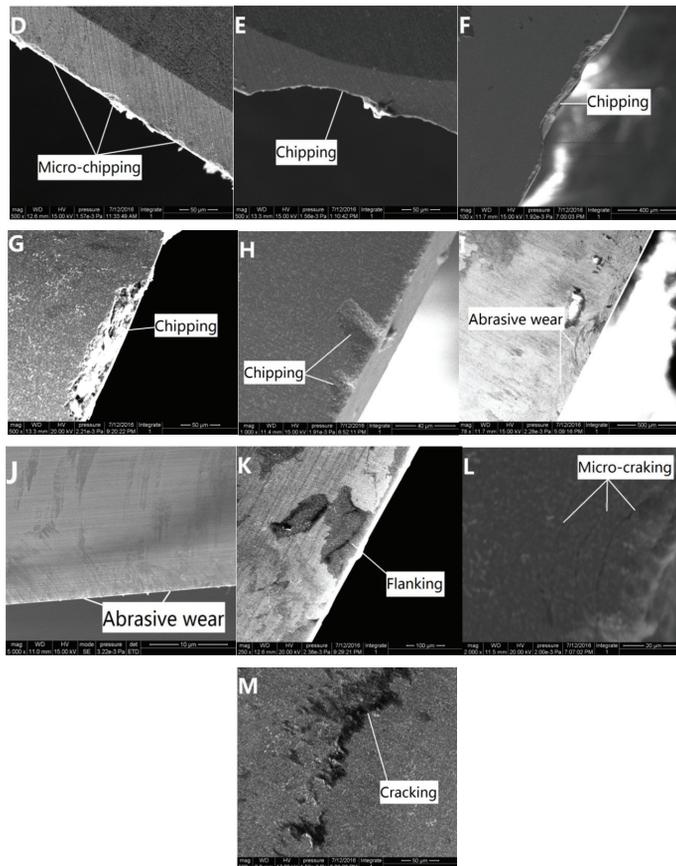


Fig. 8: The influence of cutting length on tool flank wear and wear figure of each period.

The influence of cutting speed on tool flank wear

Fig. 9 shows the effect of cutting speed on tool flank wear, which reveals the effect of high cutting speed on the flank wear was greater than that at the low cutting speed. Compared with low cutting speed, high cutting speed included high feed speed and spindle speed, it increased the processing capacity in unit time, which brought more resistance to the cutting edge and more friction between tool face and workpiece. In other words, the greater resistance and friction led to more serious tool wear. At high speed cutting processing, when encountered hard particles, which produced more impact, it is more likely to cause wear and breakage.

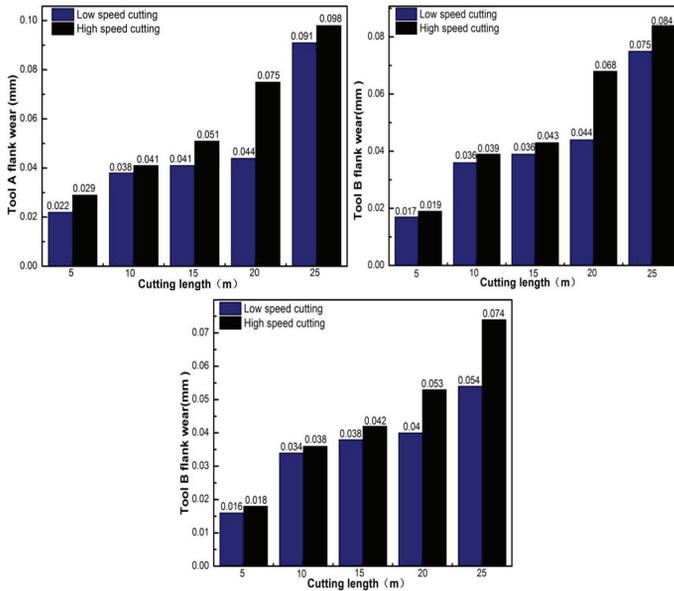


Fig. 9: The influence of cutting speed on tool flank wears.

The influence of tool parameter on tool flank wear

Fig. 10 shows the effect of tool parameter on tool flank wear, which reveals the bigger wedge angle tool and the greater flank wear. Because the smaller wedge angle tool's contact area of flank face and machined surface became smaller, which led to the smaller friction, and the flank wear decreased. Then, the smaller wedge angle meant the sharper tool and the smaller acting force on cutting layer, it also led to the smaller flank wear. However, under the same rake angle, the bigger clearance angle, the smaller wedge angle, which resulted in reduction of tool strength and increase of chipping.

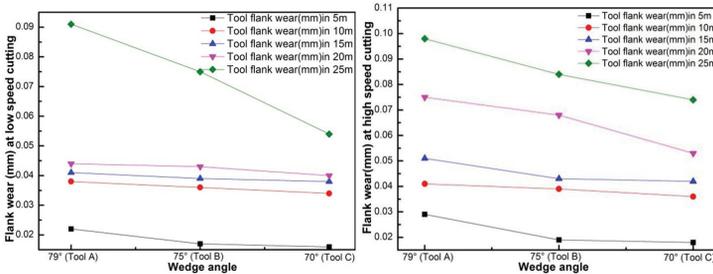


Fig.10: The influence of tool parameter on tool flank wear.

Wear pattern

Sommer et al. (2013a, b) machined the medium density fiberboard by ceramic tools showed tool wear such as grain pullout, chipping, chunking and abrasive wear. In this paper, the wear pattern was observed by SEM and analyzed by EDS, it can be obtained that the main wear pattern consists of pull-out of the grain, flaking chipping and cracking.

Pull-out of the grain and flaking

Fig. 8 B, C and K show the pull-out of the grain and flanking, Fig. 11 is microstructure of flanking layer, from the figure, it can be clearly seen that the surface is relatively flat, and the grains size is small and well-distributed, which indicates that the fracture mode is transgranular fracture mainly. The reasons leading to pull-out of the grain and flanking are as follows the first was due to the impact force between tool surface and hard particles in HDF. Secondly, with the increase of cutting length, the acting force on the grain of ceramic cutting tool increased. Finally, as the cutting temperature increased, the workpiece material was bonded to the cutting edge, when the bond material fell off, bonding force of adhesive material resulted in pull-out of the grain and flanking.

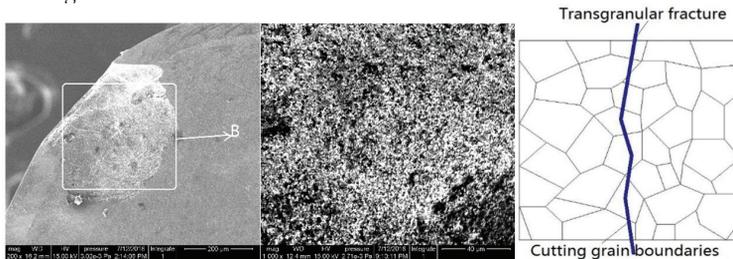


Fig. 11: The microstructure of flanking layer and model diagram.

Chipping

Fig. 8 D, E, F, G, H show chipping and Fig. 12 shows microstructure of chipping layer, from the figure, it can be clearly see its surface has obvious pits and uniform size grains, which indicate that the fracture mode is intergranular fracture mainly. In the early stage of cutting, the cutting edge was relatively sharp, and the cutting stress concentration led to chipping. Then, in cutting process, when tool crashed to the hard particles and adhesive filler in HDF, the change of cutting force or instantaneous impact load was easy to lead to chipping extremely.

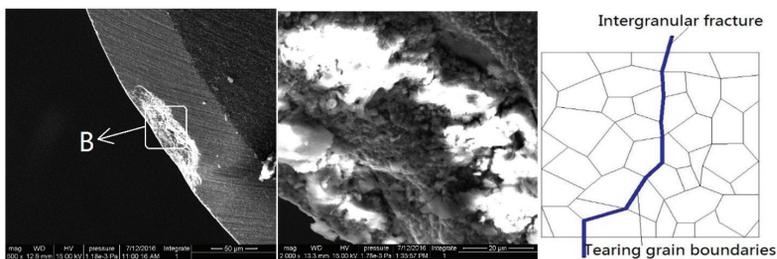


Fig. 12: The microstructure of chipping layer and model diagram.

Cracking

Fig. 8 L and M show cracking, the reasons for cracking are described as below, firstly, due to the impact force from hard particles. Then, the milling was a discontinuous process, which resulted in alternating stress. Alternating stress generates the tensile stress inside ceramic cutting tools that led to cracking. Last, milling was cyclical process, each time, when the blade cut into the workpiece, the temperature rise rapidly. When cut out, the temperature decreased, which generate alternating internal stress and led to cracking.

Wear mechanism

The wear mechanism of sialon ceramic tools were studied by Tian et al. (2013), which showed the Wear mechanism of sialon ceramic tools was adhesive wear in milling Inconel 718. For better understand tool wear well, SEM and EDS were used to study the wear mechanism too, it can be obtained that the main wear mechanism were adhesive and abrasive wear.

Adhesive wear

Based on the results of elemental analysis in Fig. 13, Ti, C, Al, Ower the major elements of alumina ceramic tool material, small amounts of elements such as K, Cl, Na were the major elements of adhesive curing agent and filler in workpiece and Ca was the element of hard point of calcium carbonate, which all don't belong to the material elements of the tools. Thus it all proved that HDF material bonded to ceramic tools, when bonding to a certain extent, the adhesive material fell off from the cutting tools and took away some cutting tool material under the action of impact and shear stress. Besides, alumina ceramic material is ionic bond and has strong adsorption capacity, eventually led to adhesive wear.

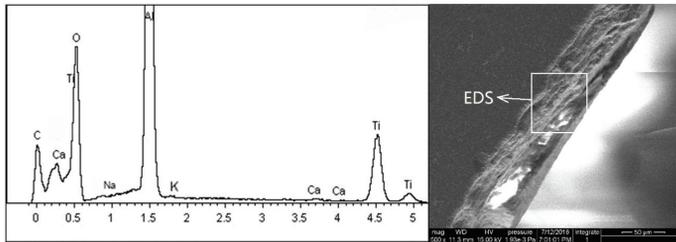


Fig.13: Adhesive wear.

Abrasive wear

From Fig. 8 J, it can be seen that there are many intensive scratches on the flank face, which is typical abrasive wear. During the milling of HDF, because of the frictional contact between the machined surface and flank face. The hard particles such as CaCO_3 , adhesive filler, generated alternating friction, slip and collision on the flank face, which caused the formation of grooves on the flank face. What's more, the alumina ceramic cutting tools toughened by TiC, and the grinding capacity of TiC is comparable to diamond, when the grains pull out, TiC scratched the flank face as well.

CONCLUSIONS

1. Under the same average chip thickness condition, whether at low cutting speed or high cutting speed, the cutting forces all increased slowly with the increase of cutting length.
2. Under the same average chip thickness condition, the tangential forces F_t and the normal forces F_r at low speed cutting were higher than that at high speed cutting.
3. Under the same average chip thickness condition, whether at low cutting speed or high cutting speed, the tangential forces F_t and the normal forces F_r decreased with the decrease of wedge angle in the same rake angle.
4. Tool flank wear increases with the increase of the cutting length.

5. The effect of high cutting speed on the flank wear was greater than that of the low cutting speed.
6. The bigger wedge angle tools lead to the serious flank wear.
7. When milling HDF, the main wear pattern consisted of pull-out of the grain, flaking chipping and cracking and the main wear mechanism are adhesive and abrasive wear.

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