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ANALYSIS OF CUTTING PERFORMANCE IN HIGH DENSITY FIBERBOARD MILLING BY CERAMIC CUTTING TOOLS

Hong Wei
Nanjing Forestry University, Faculty of Information Science and Technology
Nanjing, Jiangsu, China

Xiaolei Guo, Zhaolong Zhu, Pingxiang Cao, Baojin Wang
Nanjing Forestry University, Faculty of Material Science and Engineering
Nanjing, Jiangsu, China

Mats Ekevad
Luleå University of Technology, Division of Wood Science and Engineering
Skellefteå, Sweden

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ABSTRACT

In order to study the cutting performance of TiC reinforced Al_2O_3 ceramic cutting tools in milling high density fiberboard, the effects of cutting parameter on the cutting forces, tool wear and cutting quality were investigated. Under the condition of same average chip thickness, feed per tooth and geometry angles, firstly, the change rate of maximum cutting forces were higher than that of average cutting forces at two different cutting speeds, and the cutting forces at high speed cutting was less than that at low speed cutting. Secondly, the flank wear at high speed cutting was more pronounced than that at low speed cutting, whose abnormal wear were pull-out of grain, cracking, chipping and flanking. Thirdly, the machining quality at high speed cutting was better than that at low speed cutting. Fourthly, the tendencies of cutting forces, tool wear and surface roughness relative to cutting length were similar, but the change rates were different, especially at the initial stage. Finally, high speed cuttingare plausible to use in HDF processing, which not only improves machining quality, but also promotes production efficiency.

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

INTRODUCTION

Over the past 20 years, Chinese furniture industry has shown rapid growth, so that it makes China a leader in furniture exports (Han et al. 2009). High density fiberboard (HDF), for the furniture materials, (density of 800-1100 kg·m^{-3}), is formed by break down of 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 2007). Itis the most attractive composite material for furniture manufacturing industry with its fine texture, well resistance to deformation, strong grip for nails holding, convenient surface decoration and stable performance.

In order to meet market requirement, CNC working center is used frequently for the greatquality, high efficiency and flexibility of manufacturing process (Gawroński 2013), whose main machining methods have been conducted, such as milling, planning, routing and sanding (Saloni et al. 2011). Among them, milling is a process consisting of a linear feed movement and rotary cutting movement, which is the most common machining operation (Guo et al. 2015), and it has posted the enormous pressure and challenge for wood cutting tools.

Currently, the cemented carbide cutting toolsare used in a broadening range of wood machining with its well hardness and fracture toughness (Guo et al. 2014). However, in complicated wood machining, the wood cutting speed is 5 times faster than metal cutting at least, where the high density of cemented carbide cutting tools is dangerous because of the centrifugal force (Strehler et al. 2012). What's more, the cemented carbide cutting tools are easily corroded by the adhesive and tannins in wood products,they all reduce the tool life and the production efficiency (Sommer et al. 2013). For the higher efficiency, the diamond cutting tools with highest hardness of 10000HV are used by some enterprises, but its high price raises the cost of production seriously (Sommer et al. 2015). However, with the rapid development of toughening technology,the toughening ceramic has showed its outstanding advantage to other tool material according to theprevious studies, such as low friction coefficient that can decrease the energy consumption (Guo et al. 2013), well chemical stability to prevent the chemical corrosion wear from the adhesive and tannins in wood products (Eblagon et al. 2007), high hardness improving the wear resistance (Beer et al. 2007, Forni et al. 2008), and low density that reduces the risk caused by centrifugal force in high speed cutting (Bocanegra et al. 2009), all of which show that ceramic is a promising tool material to expand the market of wood machining.

In the long history of cutting tool studies, the cutting forces, cutting quality and tool wear have always been three important aspects that reflect cutting performance during the machining (Zhu et al. 2017). For example, the effects of cutting parameters on cutting forces werestudied and the results have showed that the cutting forces increased as wavelength, cutting depth increased (Palmqvist et al. 2003), and that they varyin the upward/downward milling (Iskra et al. 2012). A cutting forces formulation was obtained by Eyma et al. (2004), who researched the influence of wood material characteristics on cutting forces. Then, a series experiments showed that there was strong relation between the microstructure and the technological properties of the ceramics. Thegrain size affected both the possibility of shaping appropriately themicro-geometry of the milling knife and its wear behavior and cutting quality (Gogolewski et al. 2009). The surveys of Sommer et al. (2015) indicated that the wear mechanisms of ceramic cutting tools when milling medium density fiberboard was pull-out, chunking and abrasive wear. The effects of cutting speed on cutting forces and wear mechanisms of sialon ceramic cutting tools were studied by Tian et al. (2013), who suggested the resultst hatcutting forces decreased firstly and then increased with increasing cutting speed, and the wear patterns were cracks, notching, adhesion and abrasion.

In fact, the research and application of ceramic cutting tools in metal cutting is very extensive and mature (Silva et al. 2013, Zheng et al. 2012), but little information is known concerning cutting performance of ceramic cutting tools in wood machining. In this paper, the Titanium carbide (TiC) reinforced alumina ceramic cutting tools were used in up-milling HDF, under the condition of the same average chip thickness, feed per tooth and geometry angles. The effects of cutting parameteron cutting forces, tool wear and cutting quality were investigated based on the results of statistical analysis. We hope it may lead to a data that will indicate the application of ceramic cutting tools to wood machining.

MATERIAL AND METHODS

Workpiecematerial

HDF, thetesting workpiece, was supplied by Power Dekor Group Co.Ltd. China, which was a rectangular blocks with 10.7 (T)* 80(W) * 150 (L)mm, and somephysical and mechanical properties of HDF are listed in Tab. 1.

Tab. 1: The physical and mechanical properties of workpiece (the content inparentheses is the standard deviation of MOE, MOR, and density calculated from 10 data of the sample HDF).

Sample	Density (kg·m^{-3})	MOE (MPa)	MOR (MPa)
HDF	861(1.07)	4312(1.43)	49.7(0.92)

Ceramic cutting tool

Six inserts were mounted on the cuter-head with a diameter of 100 mm to balance the cutting condition. The Al_2O_3 ceramic blades were reinforced by TiC were supplied by Kyocera Trading Co.Ltd. China, whose geometry angle and mechanical properties are shown in Fig. 1 and Tab. 2.

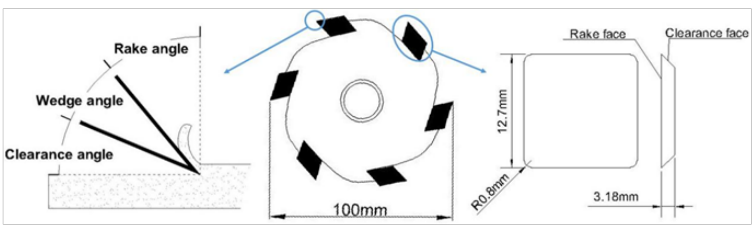

Fig. 1: The model figure of ceramic cutting tools.

Tab. 2: The geometry parameters and mechanical properties of tools.

Geometrical angle parameters			Mechanical properties		
Rake angle(°)	Wedge angle(°)	Clearance angle(°)	Hardness (GPa)	Flexural strength (MPa)	Toughness (MPa)
15	65	10	20.1	980	4.1

Experimental design

During the whole experiment, up-milling was adapted, and the cutting parameters are shown in Tab. 3.

Tab. 3: The experimental design of the same feed per tooth and average chip thickness value can be reached by changing the feed rate and spindle speed.

High cutting speed condition		Feed per tooth (mm)	The average chip thickness (mm)	Low cutting speed condition	
N ($r \cdot min^{-1}$)	U ($mm \cdot min^{-1}$)	0.333	0.047	N ($r \cdot min^{-1}$)	U ($mm \cdot min^{-1}$)
10000	20000			5000	10000

It must be noted that although only two different speed were selected, which were defined as high speed cutting and low speed cutting, the feed per tooth and average chip thickness of two cutting speed are identical. As shown in Fig. 2, ameans chip thickness, amax means maximal chip thickness, andamin means minimum chip thickness.

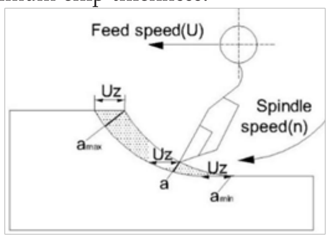

Fig. 2: The model of cutting parameters .

The formulas 1 and 2 can explain how the same average chip thickness and feed per tooth of two cutting speed were achieved, where h=2 mm and D=100 mm. In other words, the same average chip thickness and feed per tooth was obtained by the combination of high feed and spindle speed in high speed cutting condition and low feed and spindle speed in low speed cutting condition.

$$U_z = \frac{U}{n \cdot z} \tag{1}$$

$$a_{av} = \frac{U}{n \cdot z}\sqrt{\frac{h}{D}} \tag{2}$$

where: U_z - feed per tooth (mm),
a_{av} -average chip thickness (mm) ,
U - feed rate ($mm \cdot min^{-1}$)
Z- number of teeth,
n - spindle speed (rpm),
h- cutting depth (mm),
D- tool diameter (mm).

Experimental measurement

As can be seen in Fig. 3, the cutting experiment were performed with peripheral up-milling on the commercially CNC machining center of MGK01A (Nanxing group Co.Ltd, China), where the workpiece is fed against the direction of cutter rotation.

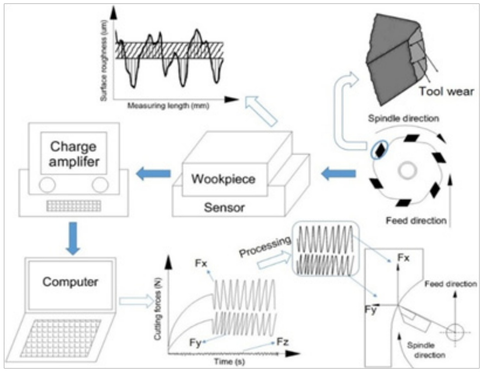

Fig 3. The experimental system diagram.

The dynamic cutting force components detected by sensor (Kisler 9257B, Switzerland) were sent to charge amplifier, which amplified and low-pass filtered to digitization. With the calculation of computer, the cutting forces *Fx* paralleled to the feed speed direction, and *Fy* perpendicular to the feed speed can be obtained. *Fz* was normal direction of the panel of *Fx* and *Fy* that was almost zero, because of cutting tools with straight edge, so only the cutting forces *Fx* and *Fy* were used as reference standard. Then, the wear volume of ceramic cutting tools were measured by vision engineering (Swift-Duo, Vision instruments Co. Ltd, England), the wear morphology was observed with scanning electron microscope (Quanta 200, FEI group Co. Ltd, USA). Finally, according to the literature review, researchers found that the arithmetic mean deviation of surface roughness (*Ra*) is the most important parameter for the evaluation of the machined surface quality. Therefore, the surface roughness measuring instrument (S-NEX001SD-12, vision instrument Co. Ltd, Japan) was employed to measure the dependent variable (*Ra*), which was set as the reference standard of machining quality.

In this paper, under the condition of the same feed per tooth, average chip thickness and geometry angles, the TiC reinforced Al_2O_3 ceramic cutting tools were used when up-milling HDF, and the aim of this experimental design was to study the effect of cutting parameter on cutting forces, tool wear and machining quality.

RESULTS AND DISCUSSION

Effect of cutting parameter on cutting performance

According to the literature review (Liao et al. 2017), cutting performance including cutting forces, tool wear, and machining quality and so on, which is affected by many factors, such as cutting speed, geometry angle, cutting length, workpiece material etc. Thus, it is importance to research the cutting performance when milling HDF by ceramic cutting tools, that is an important basis for tool design.

Effect of cutting parameter on cutting forces

As depicted in Fig. 4, the influence of cutting speed on cutting forces is obvious that Fx_{av} (the average cutting force *Fx*), Fx_{max} (the maximum cutting force *Fx*), Fy_{av} (the average cutting force *Fy*), Fy_{max} (the maximum cutting force *Fy*) at low speed cutting are all higher than those at high speed cutting. As mentioned above, the high cutting speed included high spindle speed and high feed speed, at the same cutting time, the machining capacity at high speed cutting was bigger than that at low speed cutting,the more machining capacity led to the increasing cutting temperature in contact zone between tool and workpiece, and the friction coefficient decreased with cutting temperature increased, which resulted in the decrease of cutting forces. So, high speed cutting can be adopted, which not only reduce energy consumption, but also improve production efficiency.

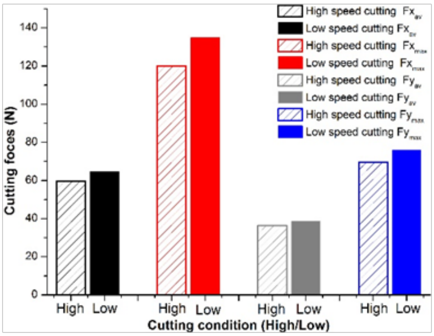

Fig. 4: The influence of cutting speed on cutting forces (cutting length=0m).

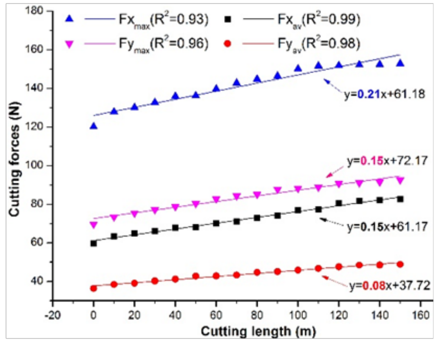

Fig. 5: The influence of cutting length on cutting forces.

Fig. 5 shows thecutting forces evolution relative to cutting length, on the one hand, the cutting forces increase slightly with the increase of cutting length.

Because the cutting edge became blunt gradually, even appeared breakage, which led to the increase of resistance in separating chips from workpiece.On the other hand, the change of Fx_{max} and Fy_{max} is more apparent than the change of Fx_{av} and Fy_{av}, as we can judge from the fitting function of cutting forces, the slope of Fx_{max} (0.21) is higher than the slope of Fx_{av} (0.15) and the slope of Fy_{max} (0.15) is higher than the slope of Fy_{av} (0.08),

Effect of cutting parameter on tool wear

The influence of cutting parameter on tool wear can be seen in Fig. 6, firstly, flank wear shows the similar tendencies with cutting length increase, the cutting edge became blunt gradually with the increase of machining capacity, which resulted from the cutting heat friction between the tool and workpiece.

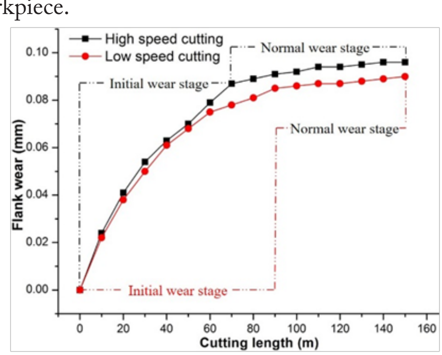

Fig.6: The influence of cutting length and cutting speedon flank wear.

In addition, cutting tool may encounter some hard particles inevitably, and the abnormal wear may occur. Secondly, at initial wear stage, the flank wear of ceramic cutting tool increase rapidly, and the initial wear stage time at high speed cutting is obviously shorter than that at low speed cutting. Finally, the flank wear at high speed cutting is more serious than that at low speed cutting. The main reason for it was that tools at high speed cutting meant more cutting heat and friction between machined surface and clearance face due to the longer cutting length in unit time, so the flank wear at high speed cutting was more serious than that at low speed cutting.

Effect of parameter on machining quality

The variation trend of the surface roughness with cutting length and cutting speed is illustrated in Fig. 7, the surface roughness of low speed cutting is higher than that of high speed cutting.

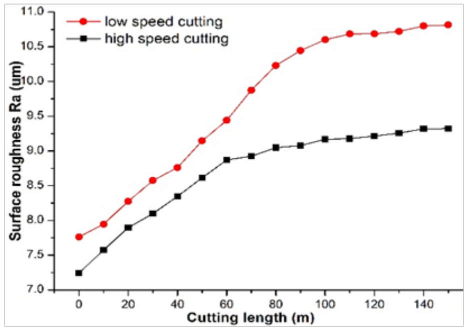

Fig. 7: The influence of cutting length and cutting speed on surface roughness as a machining quality.

The increase of cutting speed reduced the chip deformation coefficient and the friction coefficient due to high cutting temperature between tool face and workpiece, it make the cutting edge separate chip form HDF more easily. Thus, high speed cutting can used to improve cutting quality and production efficiency.

Relationship between cutting forces and cutting performance

The cutting forces of ceramic cutting tools in milling HDF was studied by Zhu et al. (2017), it showed the cutting forces has a direct influence on energy consumption and tool life. Thus, the following section will analysed the relationship between cutting forces and cutting performance.

The relationship between cutting forces andabnormal tool wear

The maximum cutting forces and tool wear degree had the same transformation trend, as given in Fig. 8, with the increase of cutting length, some significant abnormal wear can be observed on the tool face, such as pull-outof grain, chipping and flanking, it was caused bystress that came from the impact, extrusion and friction during the operation. Firstly, the HDF unavoidable contained some hard particles, such as impurities and glue. Thus, during milling, when the cutting edge contact those hard particles, the instantaneous impact force from the particles led to the abnormal wear. Then, with the increasing cutting temperature, the workpiece materials bond to the surface of tool easily, when fall off, it may take some tool materials away. Finally, in this experiment, up-milling was adapted, it wasa cyclical and disconnect process. The blade's cutting forces and temperature raised quickly as cutting into workpiece, and the cutting forces and temperature of blade decreased rapidly as cutting out workpiece, in which alternating internal stress and tensile stress were created, then it led to abnormal wear.

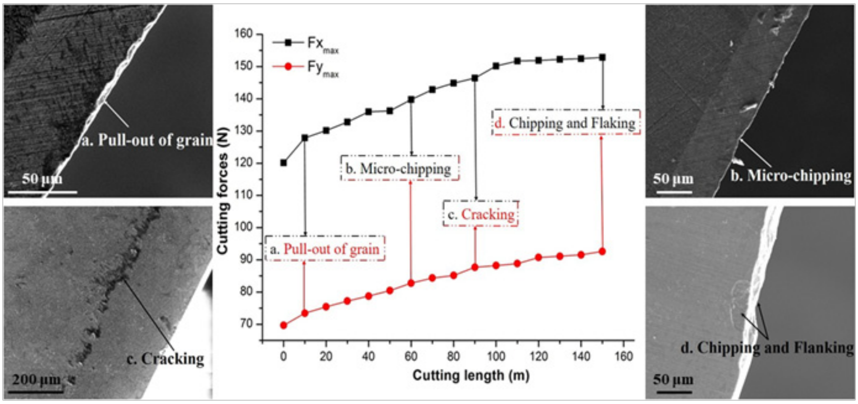

Fig. 8: The influence of maximum cutting forces and cutting length on abnormal wear shown on the micrographs of tool wear at high speed cutting.

The relationship between cutting forces and machining quality

With the increase of cutting length, the surface roughness has the similar tendency with cutting forces, as shown in Fig. 9.

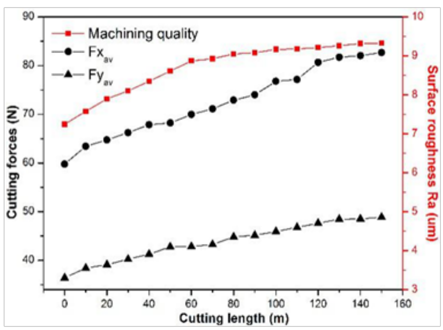

Fig. 9: The influence of cutting length on the cutting forces and surface roughness (machining quality) at high speed cutting.

Because the bigger cutting forces meant the cutting edge remove the unwanted material from workpiece more difficultly, which may result in the vibration of cutting tool. In other words, the cutting tool vibration led to the unstable cutting that led to the bigger surface roughness or poorer machining quality.

Relationship between tool wear and cutting performance

Tool wear is not only an important parameter to judge the tool life, but also affects the machining quality directly. Compared with the researches on tool wear of wood ceramic cutting tools, the relationship between tool wear and cutting performance is discussed rarely (Gogolewski et al. 2009, Zhu et al. 2107). In this section, the effect of tool wear on cutting forces and machining quality were studied.

The relationship between flank wear and cutting forces

Fig. 10 illustrates the tendency between flank wear and cutting forces are similar. As mentioned above, it is the tool wear that made the cutting forces increase. However, the change rate of tool wear is different from the change rate of cutting forces, especially at the initial wear stage.

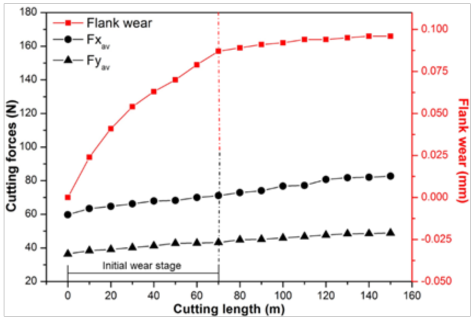

Fig. 10: The influence of cutting length on cutting forces and the flank wear (machining quality) at high speed cutting.

As shown in Fig. 10, the change rate of flank wear is higher than that of cutting forces before cutting length is 70 m obviously, which reveal although the tool wear was very fast relatively, it still has little influence on cutting forces at initial stage, because the tool didn't have the serious breakage, such as large area chipping and flanking.

The relationship between tool wear and machining quality

The relationship between tool wear and machining quality can be seen in Fig. 11, there is a noticeable and similar tendency between surface roughness and flank wear, which explain that tool wear has great influence on machining quality.

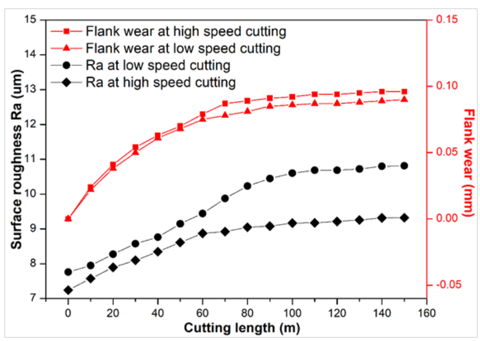

Fig. 11: The influence of the cutting length on the tool wear and surface roughness (machining quality) at high speed cutting.

The reasons are as follows: The tool nose radius became bigger gradually with the cutting length increase, and it removed the unwanted material more difficultly. Then, some abnormal wear occurred inevitably, the unsmooth cutting edge led to the poorer cutting quality. Lastly, the flank face was always in contact with the machined surface during the milling, and with the increase of cutting length, flank face became rough gradually, which led to the poorer machining quality.

CONCLUSIONS

Under the condition of the same feed per tooth and average chip thickness during machining with the TiC reinforced Al_2O_3 cutting tools, the conclusions of this experimentare as follows:

1. The change rate of maximum cutting forces were higher than that of average cutting forces at two different cutting speeds. And the cutting forces at high speed cutting were all higher than that at low speed cutting.
2. The flank wear at high speed cutting was more pronounced than that at low speed cutting, whose abnormal wear was in the fomr of: pull-out of grain, cracking, chipping and flanking.
3. The machining quality at high speed cutting was better than that at the low speed cutting.
4. The tendencies of cutting forces, tool wear and surface roughness relative to cutting length were similar, but the change rates were different, especially at the initial stage.
5. High speed cutting can be used advisedly, which not only decrease energy consumption quality, but also improve production efficiency and cutting.

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Hong Wei
Nanjing Forestry University
Faculty of Information Science and Technology
Nanjing
Jiangsu
China

Xiaolei Guo*, Zhaolong Zhu, Pingxiang Cao, Baojin Wang
Nanjing Forestry University
Faculty of Material Science and Engineering
Nanjing, Jiangsu
China
Corresponding author: youngleiguo@hotmail.com

Mats Ekevad
Luleå University of Technology
Division of Wood Science and Engineering
Skellefteå
Sweden