

The Research Progress of Machining Mechanisms in Milling Wood-based Materials

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The machining mechanisms in milling for medium-density fiberboard (MDF) and wood-plastic composites (WPC) are reviewed in this article. The study focuses on milling tool wear, chip formation mechanisms, processing stability, and machined surface roughness. The influence law of cutting parameters (cutting speed, feed rate, and cutting thickness), tool materials and geometry (rake angle, relief angle, and size parameters), temperature, and other factors on tool wear and machined surface roughness were considered. Concrete measures to improve tool life and machined surface quality are summarized as well as an online monitoring system of tool wear and machined surface roughness. Future research of tool wear and surface quality in milling wood-based materials is proposed to provide important references for wood-based materials researchers.

Keywords: Wood-based materials; Tool wear; Chip formation mechanism; Surface roughness

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INTRODUCTION

Wood-based materials can be seen everywhere in daily life, from solid wood to medium-density fiberboard (MDF) to wood-plastic composites (WPC), which are all developing in the direction of composite materials. Mainly due to the increase of the world ecological security construction requirements, there are fewer natural forest resources that can be exploited. However, MDF and WPCs make full use of leftover materials after machining, straw, and other traditional scraps, and they have a strong reproducibility and superior performance. Their market demand is increasing, and these materials will have broad applications (Shen and Jia 2010; Huang and Pan 2014). Milling is one of the most important machining methods of the secondary molding of wood-based materials. Research on critical machining mechanisms such as tool wear, chip formation mechanisms, processing stability, and machined surface roughness not only can improve tool life, but also save processing time and costs, improving processing efficiency and the surface quality of the product. This article analyzes previous research on the milling process of wood-based materials in depth. It also draws attention to specific measures to improve tool life and machined surface quality and discusses the need for future research of tool wear and machined surface roughness of wood-based materials. This article also provided the theoretical basis and reference for subsequent research and production practice.

TOOL WEAR

Wood-based material, such as MDF and WPC, can include many polymeric compounds. It also contains a variety of gluing materials and curing agents. Therefore, the cutting tool seems to be placed among a variety of media when cutting these materials. There are many factors that cause tool wear, including hard spots that may cause tool mechanical abrasion, as well as acid and alkaline media that result in a tool chemical corrosion. The cutting temperature and pressure also promote interactions between the tool and the work piece. Thus, it is a continuous disappearing process for the materials of the rake and clearance face of the tool.

Influencing Factors of Tool Wear

The wear of woodworking tools is affected by many factors, including workpiece materials, cutting parameters, tool materials and geometry (rake angle, relief angle, and size parameters), and the processing environment (temperature and cooling methods). Any parameter changes will influence the tool's performance to a certain degree, thus affecting the tool's life.

Workpiece Materials

Workpiece materials have a remarkable influence on tool wear, mainly because of the differences in hardness and toughness of different materials or the same material with different components. This can lead to different pressures in the rake and clearance face of the tool during the milling process as well as different cutting forces and temperatures that further lead to various levels of wear loss of the tool. Benlatreche *et al.* (2009) conducted milling tests on three different types of MDF. They found tool wear in milling the fireproof MDF was more serious than in milling the standard and waterproof MDFs. The tool wear that appeared in the nose width of the fireproof type was approximately three times what was observed for the standard type and four times the waterproof type. The fireproof type also had the highest degree of impurities, which could have been the cause of more serious tool wear. Saloni *et al.* (2011) investigated the tool wear condition of five commercially available wood-fiber-plastic composite materials and solid wood (eastern white pine) and they found that tool wear was the smallest when cutting the eastern white pine sample and the largest when cutting the ChoiceDek sample. The differences of tool wear in that case can be attributed to the binders, fillers, and contamination of different WPC materials.

The effects of the workpiece material on tool wear are also reflected in the chemical composition of the wood or in the gluing agent of wood-composite plates that cause the tool to be worn by chemical corrosion. Porankiewicz *et al.* (2015) assessed recesses on the rake face after milling wood laminated with polyvinyl acetate (PVA)-based glue and confirmed that sintered carbide tools were subjected to intensive tribochemical corrosion reactions (TCCR). The intensive TCCR attacked not only the binder of the tool material, but also the tungsten carbide grains, causing the tool to be gradually broken.

Tool Features

The tool materials, tool geometry, and coating technology have a certain influence on tool wear. Sommer *et al.* (2015) researched the wear conditions on four alumina-based ceramic cutting tools that had been previously manufactured by ceramic injection molding used to cut medium-density fiberboard. They found that the main wear of Al₂O₃ tools was abrasive wear and caused large-scale chipping compared to

Zirconia Toughened Alumina (ZTA) tools because of residual pores and low toughness. The edge recession of ACY tools was the lowest, which was most likely due to the best combination of grain boundary strength, hardness, and grain size. A micro-chamfering resulted in better wear behavior compared to industrially used cemented carbide (consisting of tungsten carbide and cobalt) tools. Kowaluk *et al.* (2009) researched tools that were made up of different materials and used to mill MDF. They aimed to find the tool's edge geometry that endured the least amount of tool wear. The study found that the larger the edge angle, the smaller the tool wear. At the same time, the tool material had a certain influence on the cutting edge wear. The tool wear of the carbide tool was the lightest, followed by the high-speed steel tools. The chromium (Cr) covered tools experienced the most serious wear.

Guo *et al.* (2014) studied the influence of the sharpness angle on tool wear in the up-milling of wood flour/polyethylene composites (WFPECs). The study found that the wear of the nose width was the smallest for the tool with a sharpness angle of 45° and the highest for the tool with a sharpness angle of 65°, while the wear of the edge recession was the opposite. Li *et al.* (2003) took the coating treatment on the surface of P30 carbide tools through Capacitive Voltage Divider (CVD) and Physical Vapor Deposition (PVD), used them to cut high-density fiberboard, measured the wear condition in stages, and then compared the results with the ordinary carbide tools. They found that the wear rate of the rake face of the coated and ordinary carbide tools had little difference, while the wear of the clearance face of coated tools was much smaller than an ordinary carbide tool. The quality and wear resistance of PVD-coated tools were better than that of CVD-coated tools. Gilewicz *et al.* (2013) comparatively observed the tool wear after cutting pine timber in the same conditions. These tools include uncoated (as a reference), tools with a chromium carbonitride/chromium nitride (CrCN/CrN) coating, and tools with chromium carbonitride/chromium nitride + tetrahedral carbon (CrCN/CrN+ta-C) coating. They found that the durability of the tools with a CrCN/CrN coating was more than two times that of the uncoated tools, and the durability of tools with CrCN/CrN+ta-C coating was improved by almost five times.

Machining Environments

Machining environments (temperature, cooling methods, *etc.*) also have a remarkable impact on tool wear during the wood-based material cutting process.

The effects of the cutting temperature on tool wear were observed. When the temperature rose, the hardness, toughness, and chemical stability of tool materials gradually decreased, which accelerated the tool wear (Wei *et al.* 2012). The contact area of the cutting tool and workpiece materials generated a lot of cutting heat during the cutting process. A small portion of the heat was transferred to the wood chips and removed from the cutting process, but most of the heat was transferred to the tool, which caused the abrasion resistance of the tool to decrease. Tool wear is difficult to predict accurately when the temperature distribution of the tools and how the temperature will affect the materials are not clear, especially for key areas like the cutting edge.

The temperature of the cutting edge is affected by the cutting speed, the continuity of the cutting process, the depth of cut, and the shape of the tool. Ized Horman *et al.* (2014) analyzed the temperature distribution in the blade and its influence on the blade during the wood cutting process by use of the Boundary Element Method (BEM). It was found that the higher the cutting speed, the higher the heat generated by the tool, and the more severe the tool wear. The temperature of the tool, especially near the tool nose, was higher with deeper cutting thicknesses, which led to more serious wear near the tool nose. Liu (2009) conducted some cutting temperature tests on WPCs

and Masson pine and found that shear heat had less effect on the cutting temperature, while friction heat had more of an effect. Similar methods can be used when cutting WPCs to control the cutting temperature to stay below the softening point by cutting many times at a smaller cutting depth and width, reducing the spindle speed, and increasing the feed rate, which will achieve better surface quality.

In addition, the use of appropriate cooling methods can slow the rate of tool wear. Due to the fact that liquid cooling methods are not suitable for wood cutting, researchers have made use of other cooling methods to reduce the wear loss and extend the tool's life. Stewart (2004) compared cryogenic-treated (-306 °F) C2 tungsten carbide (WC – mass fraction of 6% cobalt) with untreated carbide after cutting MDF in the same test condition. He found that the cutting force was smaller at a low temperature and the corresponding wear loss was lower. Therefore, he found that low temperatures can improve wear resistance and the life of the tool. Gisip *et al.* (2009) comparatively studied the effects of a cryogenic treatment and refrigerated air on tool wear when machining MDF. The study found that these two methods not only could reduce the temperature of the cutting zone, but also slow down the oxidation and corrosion rate of the binder, which would greatly improve the life of the tool.

Online Monitoring System of Tool Wear

Because the length of time becomes longer during the wood-based material milling process, metal materials inside the tool continue to drain from the surface and the tool edge gradually becomes dull, which reduces the cutting quality. Tool vibration and noise appeared when the tool edge was worn down to a certain extent and the machining quality became deteriorated radically, which caused severe damage to the machining center and tools (Wei *et al.* 2012). Therefore, the wear conditions of the tools were continuously checked during the cutting process and the tools were timely changed and sharpened. This process is not only cumbersome, but also time-consuming. The manual testing tool wear conditions cannot meet the needs of automatic woodworking machines. Thus, online measurement of the woodworking tool wear is an indispensable step to improve wood industrial automation.

Researchers conducted a series of online tool wear detection experiments from the aspects of digital signal and sound signal. Sun and Ai (2011) proposed a comprehensive utilization of acoustic sensing mode and force sensing mode. They took six characteristic quantities associated with tool wear that were detected by electret microphone and a Kistler dynamometer as the input signals. They utilized a back propagation (BP) algorithm to build a multi-parameter fusion model of tool wear condition monitoring. The results showed that the output value of the neural network was consistent with the measured value, and the fusion of acoustic and force signals improved the accuracy and stability of tool wear recognition. The relationship between the tool wear and the cutting noise were analyzed by Lin *et al.* (2006). An automatic tool monitoring system was designed based on a neural network that monitored the cutting tools by identifying the cutting noise signals of the tool wear. The experiment showed that the automatic tool detection system could be well applied. An adaptive control grooving system for the accurate measurement of tool wear in the milling of wood-based materials was researched by Ohuchi and Murase (2005). The system utilized a laser measuring instrument installed in a computerized numerically controlled (CNC) router to measure the cutting edge profile. The machine kept a continuous operation throughout the entire process. The results showed that the adaptive control grooving system was very effective for tool wear measurement.

RESEARCH ON CHIP FORMATION MECHANISMS AND PROCESSING STABILITY

Chip Formation Mechanisms

Wood-plastic composites have the advantages of both wood and plastic. Not only do WPCs have the natural wood-like appearance, they also have advantages, such as anti-corrosion, moisture-proof character, insect-resistance, higher dimensional stability, no cracking, and no warping. The WPC materials are heterogeneous and anisotropic, and they will be softened, melted, and even degraded at a relatively low temperature (compared with the metal material), so its processing must be different from the metal material.

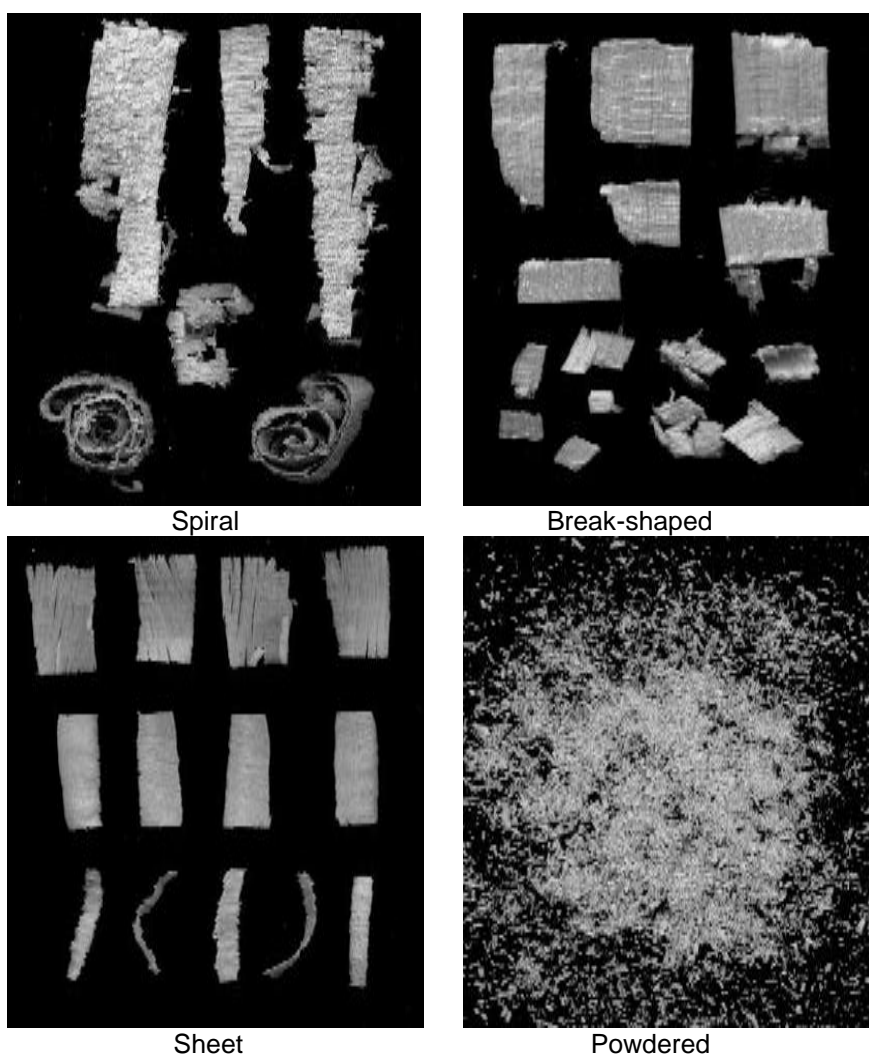


Fig. 1. Common chip shape of the wood materials

Chip formation mechanisms are the most basic scientific issue in the wood cutting process. The chip formation process has a direct effect on cutting vibrations, tool wear and breakage, chip curl and break, and machined surface roughness (Xie *et al.* 2016). Ai (2003) concluded that the workpiece materials with low hardness and high thermal physical properties (products of thermal conductivity, density, and specific heat capacity) have an easier time forming continuous chips at a large cutting speed range,

but on the contrary have an easier time forming crowded chips or unit chips. Banded chips, crowded chips, and even unit chips can transform themselves with each other in the course of changing the cutting amount. Revealing the mechanism of chip formation and defining the critical condition of different chip conversion are meaningful topics for dynamic cutting force modeling, chip breaking and cutting, reducing tool wear, and ensuring the quality of the surface processing.

Figure 1 shows the four typical chips, such as spiral, broken, sheet, and powder, that are usually produced in the cutting of the wood materials (Wei *et al.* 2016a,b). The spiral chips and broken chips are easily wrapped around the tool, which causes the damage of the tool and the workpiece, as shown in Fig. 2. Huang *et al.* (1999) noted that it is ideal to produce the complete sheet chip in the high-speed process of milling. Therefore, it was very important to obtain reasonable continuous sheet chip and to control the chip flow in high-speed machining of wood plastic composite materials.

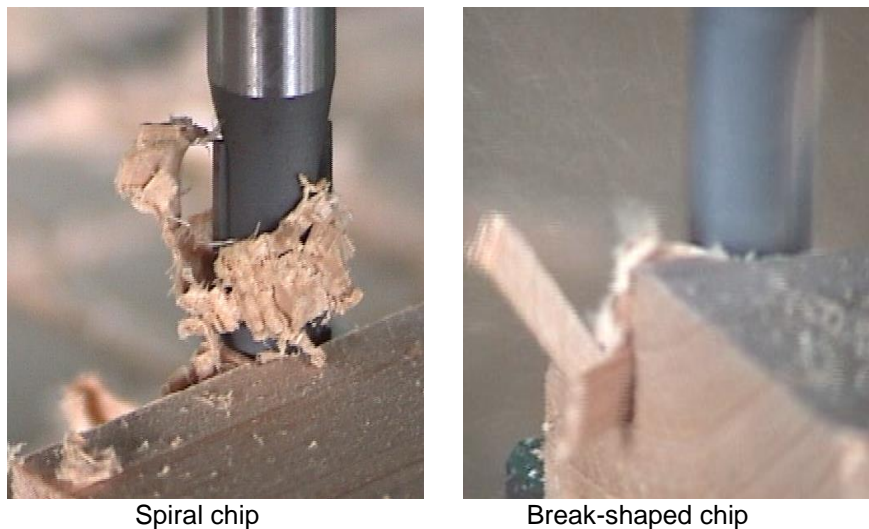


Fig. 2. The case of chips wrapped in the tool and workpiece damage

Processing Stability

Processing noise is another important problem in high-speed cutting of WPCs. There are two main causes of this processing noise. One mechanistic source of the noises is the aerodynamic noise, the other is the mechanical noise. Brooks and Bailey (1975) argue that the size of the aerodynamic noise is closely related to the shape and structure of the rotary cutter. Tanaka (1979) pointed out that the mechanical noise is caused by the operation and vibration of the machine.

MACHINED SURFACE ROUGHNESS

The surface roughness plays a very important role in many areas of the wood industry, and will make a good indication of the quality of the final product and the degree of tool wear. The amount of material removed is relatively less and the material waste rate is lower if the rough machining produces a lower surface roughness value (Murat Kılıç *et al.* 2009; Roger *et al.* 2013).

Influencing Factors of Surface Roughness

Surface roughness is one of the most important criteria to measure the surface quality. Many studies have reported that speed (cutting speed, feed rate) has a

remarkable influence on the surface roughness (Chen *et al.* 2012; Shen *et al.* 2012; de Deus *et al.* 2015). Shen *et al.* (2012) and De Deus *et al.* (2015) found that the surface roughness was inversely proportional to the milling speed and was proportional to feed rate. Chen *et al.* (2012) concluded that the cutting speed and feed rate resulted in system instability of the cutting process and substantially influenced the surface roughness of a machined workpiece.

The machined surface quality of the workpiece is not only affected by speed, but also influenced by other factors such as the temperature of the materials, tool geometry, and the cutting depth. Hernandez *et al.* (2013) measured and analyzed the surface quality of black spruce after cutting. He found that the surface quality (surface roughness, waviness, and cutting grooves) was clearly affected with the temperature of the logs. The surface quality decreased while the width and depth of the cut increased at a larger cutting diameter of the log ends. Guo *et al.* (2014) proposed that the machined surface roughness increased with the increasing sharpness angle after a feeding length of 40 m. The nose width was proportional to the surface roughness. Thus, when the nose width increased, the surface roughness increased. Keturakis *et al.* (2007) found that the surface roughness of processed birch wood increased with the increasing rounding radius of the tool. When the rounding radius of the tool reached 40 μm , the wood compressed and deformed to a remarkable extent.

Hernandez *et al.* (2014) studied the influence of cutting parameters on the surface quality of black spruce cants. The study discovered that the surface roughness decreased when the rake angle increased. The best surface roughness was obtained with 65° of rake face. Goli *et al.* (2009) observed and analyzed the appearance of chips of Douglas fir after up-milling and down-milling with different grain orientations. They concluded that the surface quality depended on the absolute grain orientation (Φ_a), while the cutting force and chip types were determined by the relative grain orientation (Φ_r). Guo *et al.* (2010) studied the dust particle size distribution and morphology of typical dust particle size in different average thickness milling conditions, and on this basis tested the surface roughness of MDF milling. The result showed that the average particle size and median diameter of MDF after milling increased with the increase of the average thickness of the milling, and the surface quality decreased with increasing surface roughness.

Real-time Detection Methods of Surface Roughness

There are currently many conventional surface roughness measuring methods. The quantitative evaluation method is divided into two categories of contact and non-contact. The contact measurement method is mainly a stylus tracing method. The stylus tracing method is used throughout the world, and it can be used to give a variety of roughness parameters and draw the surface profile curve. The contact measurement method is stable and reliable, but it has low measuring efficiency and poor real-time performance. Therefore, scholars have developed many new types of wood surface roughness measuring methods capable of real-time and online measurement, which can greatly improve the measurement efficiency.

Zhu *et al.* (2006) proposed a measuring method that uses an optical probe method to achieve three non-contact surface roughness measurements of timber by studying traditional wood surface roughness detection methods. The core of this method is a digital signal processor (DSP) TMS320F240 (Texas Instruments, Dallas, TX, USA) that can measure the signal and control the system. There are many advantages of this method that include a stable signal, fast measurement speed, and no damage to the surface of the workpiece without injury. Yin *et al.* (2008) invented a

system that realizes online detection of the machined surface roughness of wood by using microcontroller unit (MCU) to control the laser displacement sensor. The system consists of a microcontroller, analog to digital converter, a laser sensor measurement system (including the laser head and laser control device), as well as other components. The system has characteristics such as a simple structure, fast measurement speed, and detection accuracy. Iskra and Hernández (2012) invented a detection method that detected the surface roughness of white birch after cutting. They arranged a microphone at a distance from the cutting area to collect vibration signals, did analog-to-digital (AD) conversion and converted signals into a computer artificial neural network for computing, and accurately predicted the surface roughness indirectly through the vibration signal. Aguilera and Barros (2012) used a sound pressure signal to detect the surface roughness of MDF after cutting and the results indicated that measuring the sound pressure signal can effectively predict the surface roughness during the wood materials cutting process.

With the extensive application of wood materials, people's requirements with respect to the surface quality are getting higher and higher. In order to achieve the desired surface quality accuracy, it is necessary to conduct more in-depth studies of surface roughness. More advanced on-line detection devices may be developed to monitor in real time and acquire data about surface changes of workpiece in the process of milling. The surface precision ranges for different materials then can be determined by analyzing the results, which will provide the basis for actual production practice.

CONCLUSIONS

1. The design of tool structure and tool coating, and the optimization of the processing parameters to reduce the cutting temperature are key to achieving high quality processing of wood-based materials for different processing conditions and processing requirements. A great effort in the research and development of new high performance-cost ratio milling tools suitable for wood-based materials, in depth study of the coating technology, and strengthening the wear resistance of the tool through developing new high-quality coating materials is needed.
2. Due to the fact that the continuity of the traditional tool monitoring system is poor and the detection error is large, development of a new online tool wear monitoring system of wood-based materials to ensure timeless and accuracy of the analysis of tool wear in the milling process should be tested.
3. Revealing the mechanism of chip formation and defining the critical condition of different chip conversion are very meaningful to chip breaking and removal, the dynamic cutting force modeling, reducing tool wear, and ensuring the quality of the surface processing. In addition, it is important to determine how to obtain reasonable continuous sheet chips, increase unit chip quality, reduce powdered chips, and control the flow of the chips during the high-speed milling process of the wood-based materials.
4. For high-speed milling, which produces a large number of chips, a high coefficient of friction between the chip and tool and structure of the cutting tool may lead to an obstructed chip that causes tool breakage or even the entire tool specific fracture. Therefore, a big spiral angle and even straight slot milling cutter should be used to ensure smooth chip removal and to improve tool life by improving the friction performance between cutting tool and chip.

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