Cutting Forces and Chip Morphology in Medium Density Fiberboard Orthogonal Cutting

Yu Teng, Jianwen Ding, Baojin Wang, Xiaolei Guo,* and Pingxiang Cao

The influence of rake angle, cutting speed, and uncut chip thickness on cutting forces and chip morphology in medium density fiberboards orthogonal cutting was investigated. With regard to the normal cutting force and the feed force recorded, there were important variations when machining conditions were modified, or when some tool characteristics were changed. The findings led to the conclusion that there was a close relationship between the cutting conditions and chip formations as well as the cutting forces. Such forces were found to be particularly sensitive to changes in uncut chip thickness, as well as showing dependence on the cutting speed of the tools in orthogonal cutting.

Keywords: Medium Density Fiberboard; Cutting force; Chip morphology; Uncut Chip thickness; Rake angle; Cutting speed

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INTRODUCTION

Medium density fiberboard (MDF) is a widely used engineering wood product for both interior and exterior construction applications. For many applications, the perceived quality of an MDF is determined by the finish of its machined surface, which is largely influenced by the extent of tool wear and the mechanism of chip formation (Bhattacharyya *et al.* 1993; Penman *et al.* 1993; Lin *et al.* 2006). Concerning the machining of MDF, various studies have been carried out; the conclusions showed that machinability is strongly dependent on the tool characteristics, cutting conditions, and work-piece material.

Lin *et al.* (2006) described the machinability of MDF. A digital camera was used to record the deformation occurring in front of the tool tip, and scanning electron microscopy (SEM) was used to further clarify the topology of the machined surface. The study revealed that differences in MDF density had a close relationship with the machinability characteristics.

Orthogonal cutting is the machining situation where the straight cutting edge is perpendicular to the direction of the relative motion of the tool and work, and this is a basic method of the cutting process (Koch 1964). Dippon *et al.* (2000) presented a study of the orthogonal cutting mechanics of MDF. The authors assumed a Coulomb friction model on both the flank and rake faces and predicted the friction constants on both faces of the tool. Secondly, the cutting forces were expressed as functions of tool geometry, uncut chip area, and cutting constant, which were also a function of MDF density, changing along with the board thickness and the rake angle of tool.

Costes *et al.* (2003) evaluated the estimated stress and friction distributions on the rake face in the MDF cutting process. Also using orthogonal cutting, tools with restricted tool-chip contact length were studied on a computer numerical control lathe, and an approach to evaluate the friction and normal load distribution on the rake face of the tool for cutting MDF was presented.

Aguilera *et al*. (Aguilera 2009; 2011; Aguilera and Barros 2011) set a series of experiments to investigate the MDF rip sawing, with emphasis placed on the surface roughness of the processed panel. The findings led to the conclusion that there was a close relationship between cutting parameters and surface roughness, being greatly influenced by changes in specific gravity within the profile of the panel, and in particular to changes of mean chip thickness. The acoustic pressure signal was also investigated and was demonstrated to be a promising potential method for monitoring wood based material processes, as it could predict the resulting surface roughness of the machined boards together with the effect of the feed rates and the cutting modes on MDF.

Davim *et al.* (2008) investigated the influence of cutting parameters (cutting speed and feed rate) on surface roughness in MDF milling. End milling of MDF panels was carried out, and it was found that the surface roughness decreased with an increase of spindle speed and increased with the feed rate. The spindle speed played a significant role on the surface roughness as a function of material removal rate (MRR), which showed that using high cutting speed in milling MDF was an important factor. Aguilera *et al*. (2000) focused on the influence of MDF material in a routing operation. Tool-Material Couple methodology was applied to define the optimum machining conditions for a tool cutting MDF material for a maximum tool life, as well as a qualified surface roughness.

Davim *et al.* (2007a) carried out an experimental study dealing with cutting parameters (cutting speed and feed rate) on delamination of the blind hole in drilling MDF. Later, Davim *et al.* (2007b) studied delamination in drilling of MDF using response surface models. Gaitonde *et al.* (2008a) researched the prediction and minimization of delamination in drilling of MDF using response surface methodology and Taguchi design. They also (Gaitonde *et al.* 2008b) studied the optimization in drilling of MDF to minimize delamination by using the methodology of Taguchi optimization method. All of the studies agreed with the conclusion that a combination of low feed rate with high cutting speed is necessary to minimize delamination in drilling of MDF.

Guo *et al.* (2014) investigated the cutting forces and chip morphology during wood plastic composites orthogonal cutting. Statistical results indicated that the parallel cutting force was most significantly influenced by chip thickness and that the normal cutting force was significantly influenced by chip thickness and rake angle.

The aim of this paper was to determine the cutting force required to cut medium density fiberboard (MDF) and to study its relationship with the chip morphology when the cutting parameters change.

MATERIALS AND METHODS

Materials

The MDF panels tested came from a set having 7.8 mm thickness, which is equal to the cutting width, MDF board commercial-type, being processed into a disc with a diameter of 200 mm. For the machining trials, 25 samples were extracted randomly from one board. The bending strength was tested according to the GB/T 6569-86 in the three-point bending mode at a cross head of 0.5 mm/min and with a span of 30 mm. The specimen size for bending test was 35 mm (L) × 4 mm (W) × 3 mm (T). Five specimens were tested in each run. Some mechanical and physical properties of the MDF panels are described in Table 1.

As the manufacturing process of MDF, there is a density profile across the thickness of the board. According to the study of Boucher *et al*. (2007) and Michaud *et al*. (2003), a density of MDF board 768 kg/m^3 used in our experiments showed a comparatively smooth density profile. And in the research of Lin *et al*. (2006) the densities of two types MDF boards were low-density (740 kg/m^3) and high-density panels (1000 kg/m^3); those changes in density were much larger than the density variation of a single panel in the present tests. So the influence of density profile along the board thickness was ignored in the present work.

The specimens obtained were placed in a climatization chamber with a temperature of 23 ºC and a relative humidity of 75% until they reached unchanging weights. After this stage, the specimens were placed in plastic bags in order to maintain the humidity and were kept for the test.

Table 1. Physical and Mechanical Properties of MDF Panels Tested

Material	Density [kg/m^3]	Moisture content [%]	Bending Strength [MPa]	Elasticity Modulus [MPa]
MDF	768	7.8	40	2850

Methods

Cutting force and cutting process measurement

The samples were machined on a lathe machine with variable cutting speed and feed rate, as shown in Fig. 1. The cutting forces were measured with a piezoelectric dynamometer Kistler 9257 B coupled to a 5019 A charging amplifier and to a computer fitted with an acquisition card and the software for signal treatment. When the cutting tool cut the work piece, only the normal cutting forces (F_c) and the feed force (F_f) were measured in this series cutting experiments.

A high speed camera, an i-speed 3 camera of Olympus with a frame rate of 4000 fps compared to the resolution of 912×684 and exposure time of 1/10000 s, was used to record the machining process and chip form. Photos of chips produced in these experiments were also taken and analyzed.

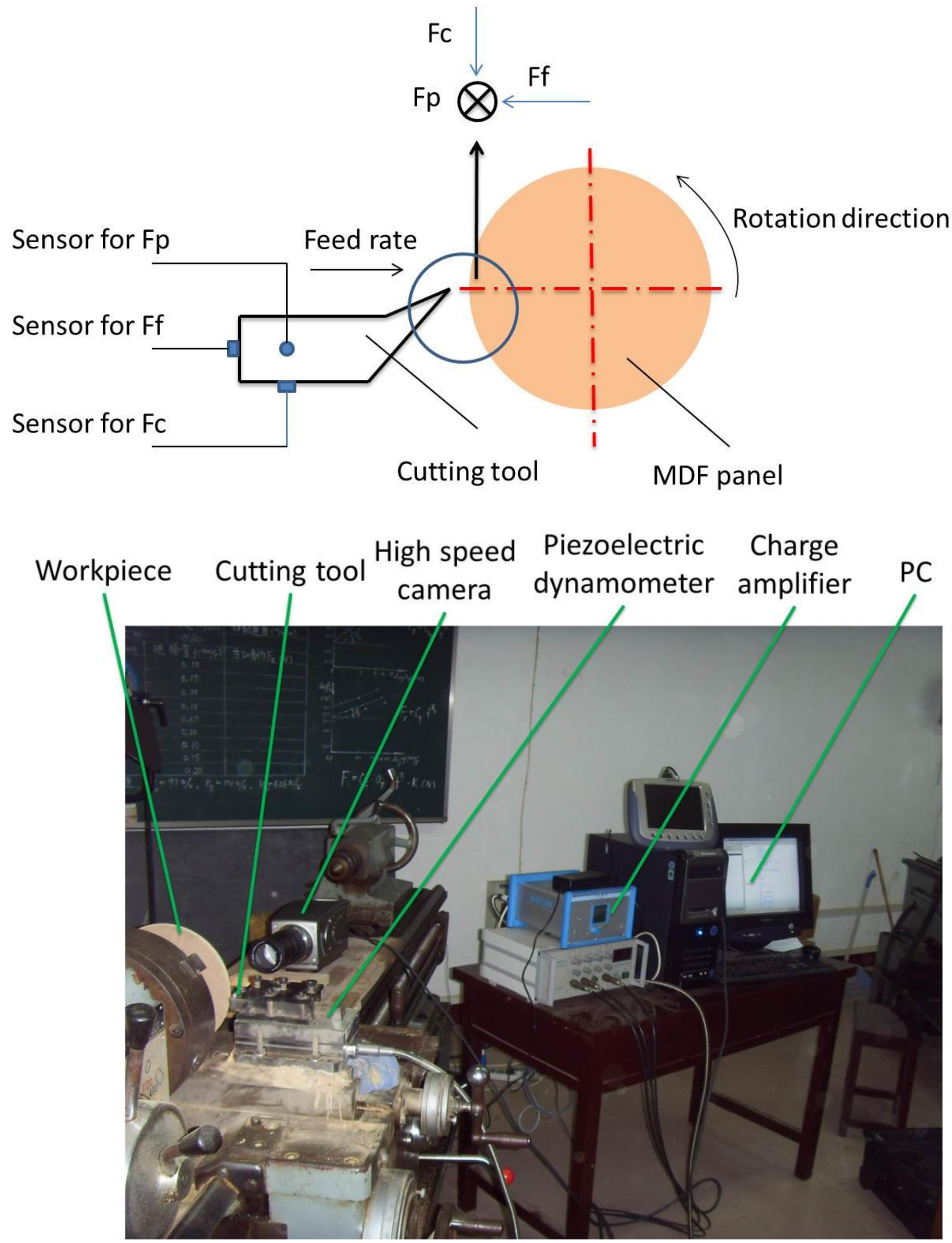
Plan of the experiment

A full factorial experimental design was established where the main variables were the uncut chip thickness (h, three levels: 0.027, 0.1 and 0.61 mm), the rake angle of tools (γ_f, three levels: 5, 15 and 30°), and the cutting speed (v_c, three levels: 0.84, 1.67 and 3.36 m/s), as shown on Table 2.

Table 2. Assignment of Levels to Factors

Level	Uncut chip thickness h [mm]	Rake angle γ_f [°]	Cutting speed v_c [m/s]
1	0.027	5	0.84 [80 r/min]
2	0.1	15	1.67 [160 r/min]
3	0.61	30	3.36 [320 r/min]

Analysis of variance (ANOVA) was carried out by using the software of Statistical Product and Service Solutions (SPSS version 20.0) in order to study the influence of uncut chip thickness, rake angle, and cutting speed on the total variance of the results.



(a)

(b)

Fig. 1. Experiment Setup: (a) Schematic diagram; (b) Picture

RESULTS AND DISCUSSION

Analysis of Normal Cutting Force

Influence of uncut chip thickness, rake angle, and cutting speed on the normal cutting force

Table 3 shows the results of both of the normal cutting force and feed force for the full factorial experiment.

Table 3. Full Factorial Experimental Plan

Test No.	h [mm]	γ_f [°]	v_c [m/s]	F_c [N/mm]	F_f [N/mm]
1	0.027	5	0.84	56.12	162.1
2	0.027	5	1.67	87.86	91.86
3	0.027	5	3.36	87.79	92.05
4	0.027	15	0.84	24.66	141.1
5	0.027	15	1.67	42.48	65.12
6	0.027	15	3.36	43.61	66.15
7	0.027	30	0.84	27.11	116.1
8	0.027	30	1.67	49	69.6
9	0.027	30	3.36	44.9	68.97
10	0.1	5	0.84	73.52	88.89
11	0.1	5	1.67	83.71	105.1
12	0.1	5	3.36	87.67	98.44
13	0.1	15	0.84	21.02	162.4
14	0.1	15	1.67	51.17	92.86
15	0.1	15	3.36	43.02	78.28
16	0.1	30	0.84	45.37	76.98
17	0.1	30	1.67	39.38	69.6
18	0.1	30	3.36	55.49	71.65
19	0.61	5	0.84	49.9	220.7
20	0.61	5	1.67	50.12	226.8
21	0.61	5	3.36	58.02	229.9
22	0.61	15	0.84	14.57	207.5
23	0.61	15	1.67	13.02	189.1
24	0.61	15	3.36	7.47	225.8
25	0.61	30	0.84	17.07	182.7
26	0.61	30	1.67	15.94	181.2
27	0.61	30	3.36	12.18	189.7

Notes: Normal Cutting Force (F_c), Feed Force (F_f)

Figure 2 shows the normal cutting force of different cutting speed changes with the changes of rake angle (γ_f) and chip thickness (*h*).

It can be seen that in Fig. 2, at a comparatively high cutting speed, higher than 1.67 m/s in this test, the normal cutting force had little connection with the cutting speed. Moreover, lines in Fig. 2 with the cutting speed of 1.67 and 3.36 m/s indicated that the normal cutting force increased approximately linearly with the increasing of the uncut chip thickness (*h*) and decreased slightly with the increasing of rake angle (γ_f).

However, when the cutting speed was at a very low level (0.84 m/s in Fig. 2), the normal cutting force changed dramatically with the increasing of uncut chip thickness (*h*). The reason may be explained by the study of Dippon *et al*. (2000), which showed that the pressure exerted by an uncut chip on the rake face mainly dominated the force on the rake face.

With the small chip thickness, low cutting speed, and the elasticity of the MDF fiber itself together with the adhesive used in the MDF manufacturing process, chips are not very easy to fracture and connect with the uncut chip, and this factor tends to strengthen the normal cutting force.

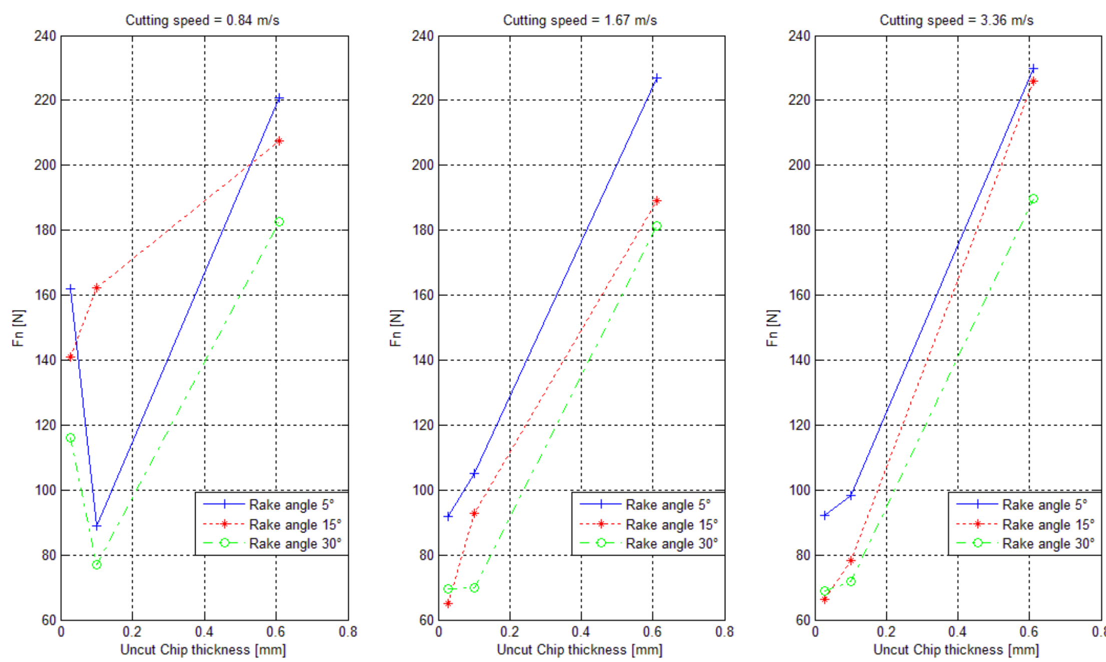


Fig. 2. Effect of parameters on normal cutting force of MDF in orthogonal cutting

ANOVA for Normal cutting force

The analysis of variance was carried out in order to acquire the statistical significance of the variables (h, v_c, γ_f) and their interactions on the normal cutting force in orthogonal cutting of MDF panels for a level of significance of 5%.

As shown in Table 4, for the MDF cutting, uncut chip thickness, cutting speed, rake angle, together with the interaction between chip thickness and cutting speed had statistical contributions on the normal cutting force, according to the p-value of less than 0.05 and the F-value of greater than the $F_{0.05}$.

Table 4. Results of ANOVA for Normal Cutting Force

Source	SS	Df	MS	F	Sig.	$F_{0.05}$	
h	73348.262	2	36674.131	140.395	0.000	5.14	*
v_c	4767.202	2	2383.601	9.125	0.009	5.14	*
γ_f	4892.830	2	2446.415	9.365	0.008	5.14	*
$h * v_c$	5033.557	4	1258.389	4.817	0.028	4.53	*
$h * \gamma_f$	1513.401	4	378.350	1.448	0.303	4.53	NS
$v_c * \gamma_f$	1609.928	4	402.482	1.541	0.279	4.53	NS
Error	2089.767	8	261.221				
Total	565460.187	26					

R^2= 99.6% ; R^2(Adj) = 98.8%; * Significant; NS non-significant
SS - Sum of Squares; MS – Mean Square; Sig - Significance

Analysis of Feed Force

ANOVA for Feed force

The analysis of variance was carried out in order to acquire the statistical significance of the variables (h, v_c, γ_f) and their interactions on the feed force in orthogonal cutting of MDF panels for a level of significance of 5%.

Table 5. Results of ANOVA for Feed Force

Source	SS	Df	MS	F	Sig.	$F_{0.05}$	
h	4472.749	2	2236.374	52.302	0.000	5.14	*
γ_f	9239.570	2	4619.785	108.043	0.000	5.14	*
v_c	852.363	2	426.182	9.967	0.007	5.14	*
$h * \gamma_f$	24.921	4	6.230	0.146	0.960	4.53	NS
$h * v_c$	623.216	4	155.804	3.644	0.056	4.53	NS
$\gamma_f * v_c$	158.740	4	39.685	0.928	0.494	4.53	NS
Error	342.070	8	42.759				
Total	69240.025	26					

R^2 = 97.8% ; R^2(Adj) = 92.9%; * Significant; NS non-significant
SS - Sum of Squares; MS – Mean Square; Sig - Significance

Table 5 shows the results of ANOVA analysis for the feed force. As can be seen in Table 5, uncut chip thickness, cutting speed, and rake angle had statistical significance with respect to the feed force, since p-value of these factors was less than 0.05, and the F-value of these factors was greater than $F_{0.05}$.

Influence of uncut chip thickness, rake angle, and cutting speed on the feed force

Figure 3 shows the feed force of different cutting speed changes with the changes of rake angle (γ_f) and chip thickness (h).

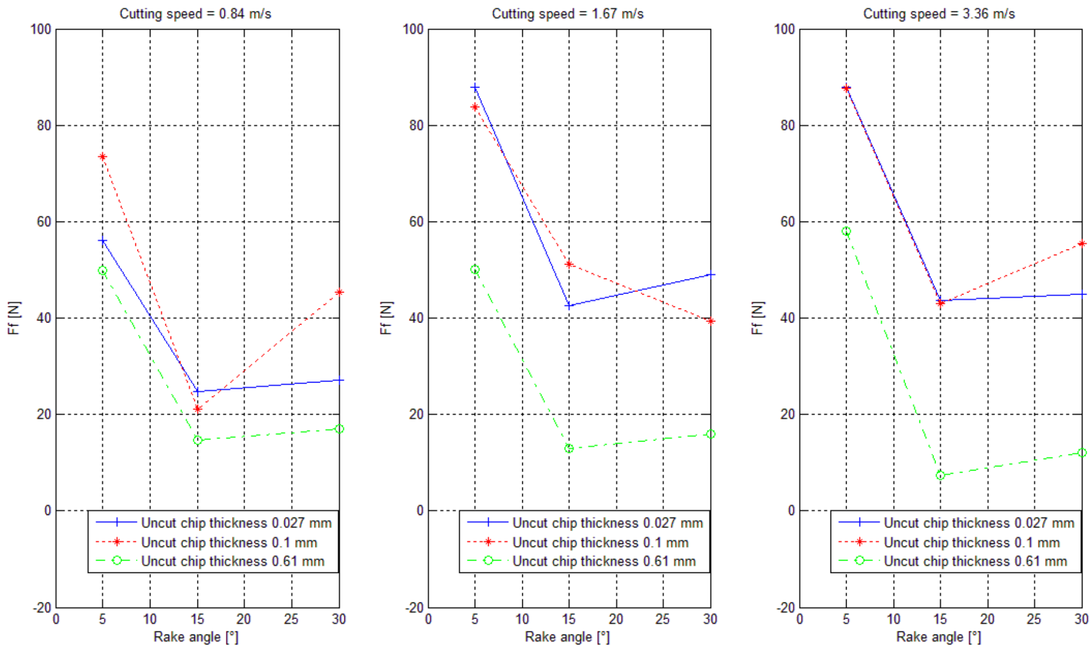


Fig. 3. Effect of parameters on feed force of MDF in orthogonal cutting

From Fig. 3 it can be seen that, with the increasing of the rake angle, the feed force of MDF cutting mainly decreased in magnitude at the beginning and then changed slightly. Take the cutting speed of 1.67 m/s for example, the feed force was decreased by more than 30 N, with the rake angle changing from 5^o to 15^o, and then changed less than 10 N, though the rake angle changed from 15^o to 30^o. This may be the reason that with rising of rake angle, the chip contact area changed, which is in agreement with the study of Costes *et al.* (2003), indicating that the cutting edge was loaded most within 0.1 mm, and diminished almost completely after 0.25 mm when machining MDF.

It can also be found that, at the uncut chip thickness less than 0.1 mm in this test, there were little differences found on feed force when the uncut chip thickness changed. Meanwhile, the uncut chip thickness increased more than 0.1 mm (0.61 mm in this experiment), and the feed force decreased obviously, especially under the large cutting speed (cutting speed of 3.36 m/s for example). This revealed that the chip thickness had great contributions on the feed force.

Analysis of Chip Morphology

The MDF cutting process is mainly influenced by fracture and compression of MDF chips between the incoming material and the rake angle of tool (Costes *et al*. 2003). Hence, the chip morphology was studied in this experiment. In the present work, the resulting chip form was obviously influenced by the cutting conditions. Photos of the typical moments recorded during the chip forming process at uncut chip thickness of 0.027, 0.1, and 0.61 mm, respectively, at rake angle of 5, 15, and 30°, respectively, at cutting speed 0.84, 1.67, and 3.36 m/s, respectively, are shown in Table 6(a, b, c).

From Table 6(a, b, c) it is apparent that the forming process of all kinds of chips can be clearly captured. Like Table 6(c), the coiled chip type can be easily found in the picture. All kinds of chip morphology can also be divided by using the pictures taken by high speed camera, which will be explained in the following pages.

Table 6a. Photos by i-SPEED Camera at Uncut Chip Thickness of 0.027 mm

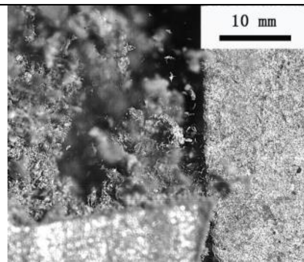
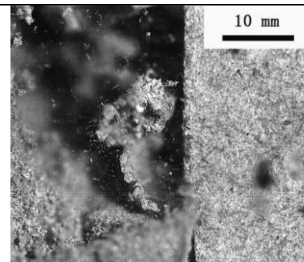
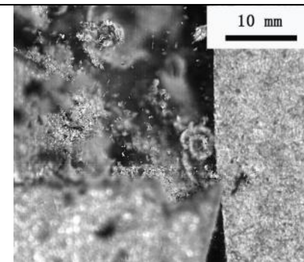
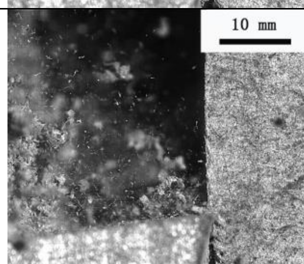
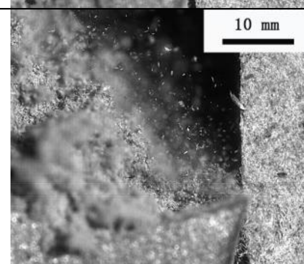
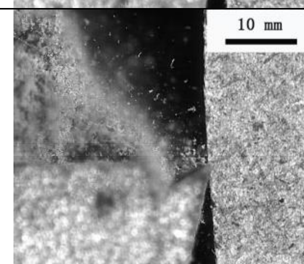
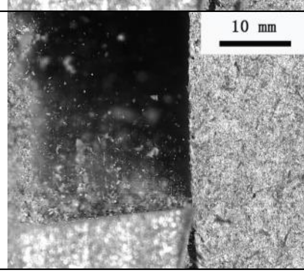
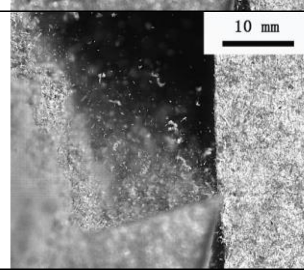
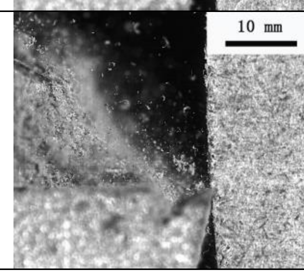
v_c \ γ_f	5°	15°	30°
0.84 m/s			
1.67 m/s			
3.36 m/s			

Table 6b. Photos by i-SPEED Camera at Uncut Chip Thickness of 0.1 mm

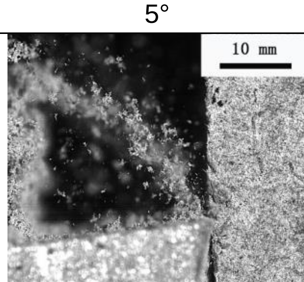
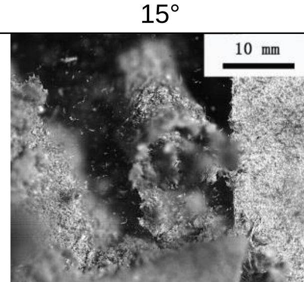
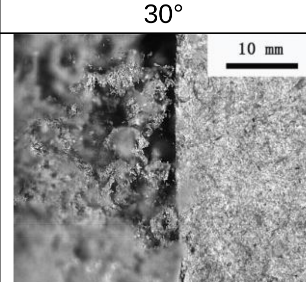
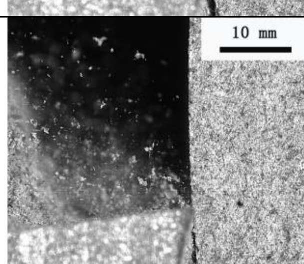
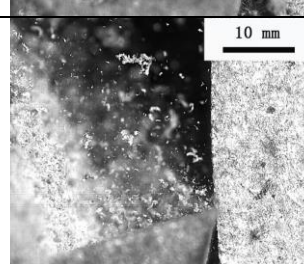
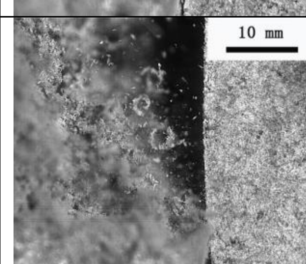
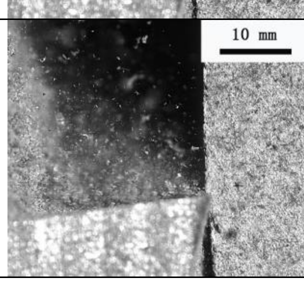
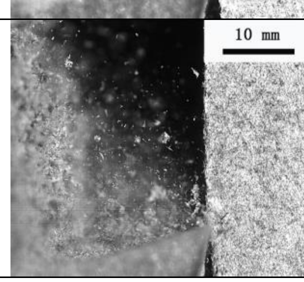
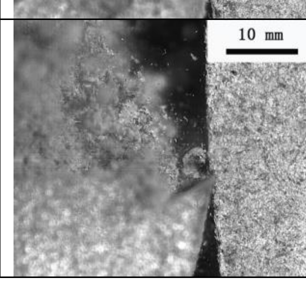
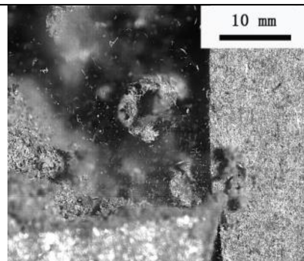
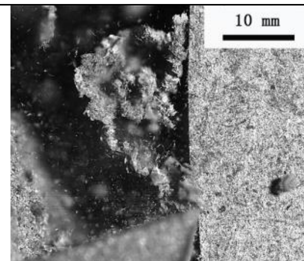
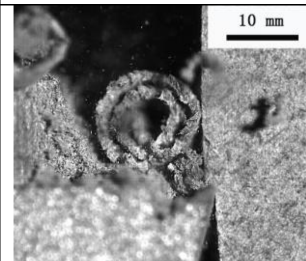
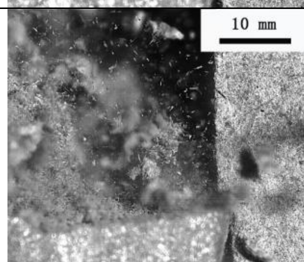
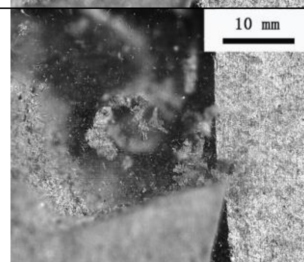
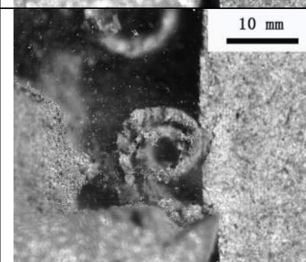
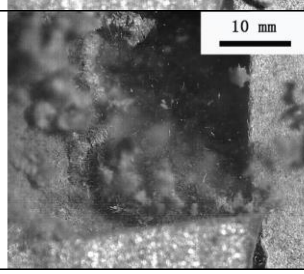
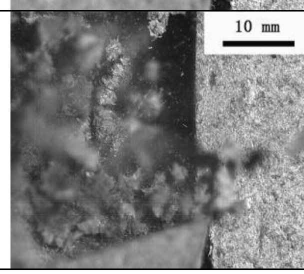
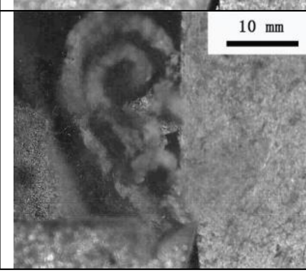
v_c \ γ_f	5°	15°	30°
0.84 m/s			
1.67 m/s			
3.36 m/s			

Table 6c. Photos by i-SPEED Camera at Uncut Chip Thickness of 0.61 mm

v_c \ γ_f	5°	15°	30°
0.84 m/s			
1.67 m/s			
3.36 m/s			

When cutting the MDF panel, various types of chips obtained for the full factorial experiment can be divided into three typical chip forms, namely coiled chip, granular chip, and dust. Typical examples of all these three classified chip forms are shown in Fig. 4 by the usage of the photos of macroscopic view. The coiled chip (Fig. 4(a, b)) is the one that continuous chip formed into one roll or two rolls connected with each other. The granular chip (Fig. 4(c, d)) is the one that continuous chip splits into pieces, and these small chip pieces are easy to break out into more tiny particles. The dust (Fig. 4(e, f)) includes those chips that cannot be clearly classified because of their small sizes.

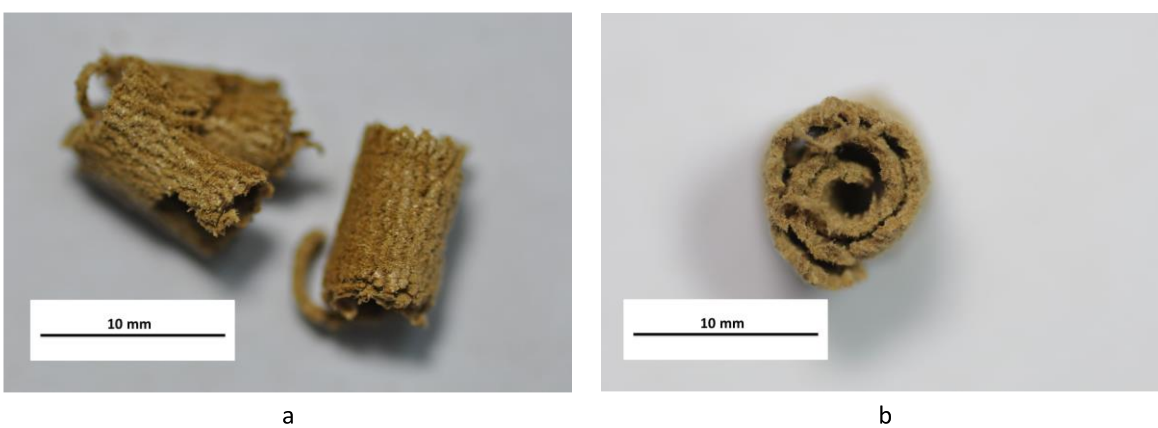


Fig. 4 (a, b). Photos of Macroscopic View of Classified Chip Form Examples of Coiled Chip (a, b) γ_f = 30°, h = 0.61 mm, v_c = 0.84 m/s

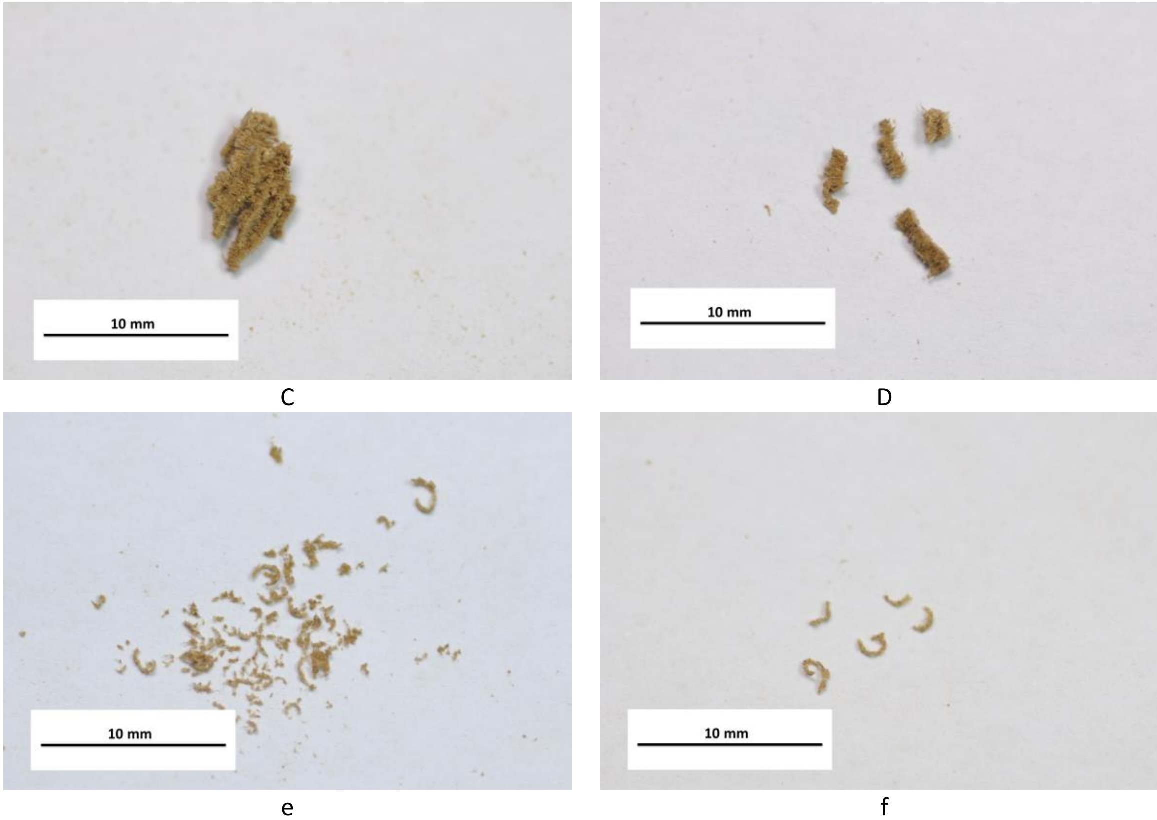


Fig. 4 (c, d & e, f). Photos of Macroscopic View of Classified Chip Form
Examples of Granular Chip (c, d) γ_f = 15°, h= 0.61 mm, v_c = 3.36 m/s
Examples of Dust (e, f) γ_f = 15°, h = 0.1 mm, v_c = 3.3.6 m/s

Cutting forces of composite materials are significantly influenced by chips produced during the cutting process (Davim *et al.* 2009; Su *et al.* 2003).

From Table 6, it can be seen that it was very easy to produce the coiled chip at large uncut chip thickness. The number of coiled chips at an uncut chip thickness of 0.61 mm was more than that of 0.1 mm, by comparing Table 6(a) and Table 6(c). This finding indicated that uncut chip thickness had a significant impact on chip form similar to the trend of its impact on the cutting force.

However, coiled chips were also produced when cutting MDF at cutting speed of 0.84 m/s, whatever the uncut chip thickness was within the tested range. This fact may be caused by ductile behavior of MDF, which kept the processing chip away from fracture and moved on the rake face as a rigid body. A rigid object, when connected with the rake face and uncut chip, increased the pressure on rake face, and the pressure on the rake face mainly dominated the cutting force. These findings also indicated that ductile properties of materials at a low cutting speed in orthogonal cutting can lead to a higher normal cutting force. This fact coincided with the results of normal cutting force above.

Further, granular chips were obtained at uncut chip thickness of 0.1 mm and 0.61 mm when cutting MDF boards. This may be due to brittle behavior of MDF. From Table 6(c), when the cutting speed was 0.84 m/s, with the decreasing of rake angle, the chips produced tended to be shorter or smaller. The effect may be a result of the increasing of chip thickness and decreasing of rake angle in MDF cutting, which transforms the cutting mode from ductile cutting to brittle cutting. So it can be thought that uncut chip thickness and rake angle had a significant impact on the chip form when cutting MDF.

CONCLUSIONS

1. Statistical results indicated that the changes of rake angle, uncut chip thickness (feed rate), cutting speed, and the interaction of uncut chip thickness and cutting speed had very significant influence on the normal cutting force, while the variations of interaction of rake angle and uncut chip thickness, as well as interaction of rake angle and cutting speed made little contribution to it.
2. Statistical results indicated that the changes of rake angle, uncut chip thickness (feed rate), and cutting speed greatly influenced the normal cutting force, while the variations of interactions of rake angle, uncut chip thickness, and cutting speed, respectively, had little contributions to it.
3. Chip forms of MDF cutting could be divided into three typical types. Low cutting speed or high chip thickness tended to produce coiled chips. Granular chips were more likely obtained at large chip thickness and small rake angle.

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