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Influence of the milling tool setup on occupational safety in furniture making

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One of the most serious causes of accidents in furniture making is kickback of machined material. The aim of this study was to determine the influence of the milling tool setup on hazards associated with kickback in furniture making. The speed of kickback was accepted as the measure of these hazards. The experiment involved controlled changes in milling tool setup, projection of cutting knives over the body of the milling tool, number of cutting knives and clearance angle. Multifactor analysis of variance was applied to the results of individual experiments, showing statistically significant factors and their interactions. Inspection and analysis of traces left by the cutting knives of the tools on the test pieces made of wood materials supported inferential statistics. The obtained results verified some common opinions and ideas on the impact of the milling tool setup on the hazards resulting from kickback in furniture making.

Keywords: kickback; ejection; milling; occupational safety; furniture making; hazards

1. Introduction

One of the main causes of accidents in the furniture-making industry is the ejection of the workpiece. The need for actions to prevent the risk caused to the operator and potentially exposed persons by this ejection is noted, *inter alia*, by the International Labour Organization [1], in its guidelines, and by Directive 2006/42/EC [2]. In the British guidebook [3], the ejection (or kickback) is stated as a dangerous phenomenon common for hand-fed machinery, in particular for circular saws, planing machines and hand-fed vertical spindle moulding machines.

First mentions of vertical spindle moulding machines date back to the mid-19th century. The encyclopaedic description of the machine structure from that time refers to cutterheads of different sizes (with cutting edges attached to them) located on adjusted, vertical spindles of the moulding machine, and to guards above the heads, which protect the operator [4]. The moulding machines were used without guides and the body of cutterheads had a square cross-section at the beginning. The first cutting tools with a cylindrical body shape appeared only around 1901 in Germany and England.

It has been long thought that the risk could be limited by the use of appropriate cutting tools with a structure limiting the rate of the feed per cutting edge [5]. So-called limited cutter projection tooling (LCPT), reducing the risk of injuries in the event of accidental contact with the moving cutting tool, is recommended by the guidebook [6] and Standard No. BS 6854-3:1989 [7]. According to this standard, the reasons for limiting the projection of the cutting edges outside the tool body involve, apart from the increased probability of damaging the tool with a large blade projection and the severity of injuries which can be sustained by contact with such a tool, also greater probability of occurrence and aggressiveness of the kickback.

Standard No. EN 847-1+A1:2008 [8] divides cutters into those designed for milling in mechanically fed and manually fed machines, marked MEC and MAN, respectively. There have been additional requirements prepared for the latter type, in particular those regarding the cylindrical shape of the body and sizes of chip clearances as well as the maximum cutter blade projection outside the body. However, Standard No. EN 847-1+A1:2008 does not provide any reasons for these requirements. It thus seems necessary to test experimentally the significance of the effect of the setup of cutter blades on the actual level of occupational safety during the process of milling wood materials in furniture making.

The investigations of accidents during woodworking [9–11] indicate that in many accidents when an injury is sustained due to direct contact of the operator's body part with the operating cutting tool, the kickback of the workpiece is an indirect cause that triggers the sequence of events leading to the accident. As a result of the kickback, the workpiece is abruptly ejected from under the hands and the operator loses his/her balance. Then, severe finger and hand injuries are sustained, as a result of contact with the rotating cutting tool.

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The severity rate of injuries depends not only on the ejection itself, which is caused by a sudden increase in components of the cutting and thrust forces in the direction of the ejection. It is beyond the operator's ability to balance these, for a variety of reasons. The consequences of this imbalance become more dangerous with greater surprise of the operator, i.e., with sharper (quicker) movement of the ejected piece. Possible injuries sustained as a result of the accident are considered to be the proper determination and measure of the hazard [12]. Therefore, the kickback speed may be adopted as the most reasonable measure of the hazard in this type of accident.

This article presents the results and analysis of experimental tests to determine the effect of the setup of the cutterhead blades during the process of milling wood materials on the kickback speed.

2. Materials and methods

During the tests a test stand constructed on the basis of the assumptions of Standard No. EN 847-1:1997 [13] was used. The test stand (Figure 1) comprises a wood vertical spindle moulding machine with stepless adjustment of spindle rotations measured by an incorporated tachometer.

There is a pneumatic-mechanical unit installed in the moulding machine, which is controlled by a wired remote control. This unit elastically presses the wood workpiece to the table, the cutting tool and the guides of the moulding machine with the forces specified in Standard No. EN 847-1:1997 [13]. The pressure is applied by feet and springs shifted by air actuators. Next, the actuator triggers the feeding movement of the sample during which the milled sample is ejected in the specified cutting conditions.

The course of each experiment was recorded at a filming speed of 250 frames/s with the use of a high-speed camera (InLine 1000; Fastec Imaging, USA) and FIMS version 3.0.5. The piece movement speed was determined on the basis of the recordings played in MIDAS Player version 2.2.1.1. The kickback speed (V) was determined as the mean of 10 repeated kickback tests performed for the given cutting conditions. The projection of cutter blades outside the cutterhead, the number of cutting blades as well as the cutting speed and the workpiece were considered in the experiments as independent variables. The test results were subject to multifactor analysis of variance, which allowed determination of the statistical significance of the individual factors effect. A standard η^2 factor was adopted as the measure of the size of the experimental effect, calculated as the quotient of the sum of squares of deviations connected with a given factor and the total sum of squares of deviations [14].

The statistical conclusions were supported by the test and analysis of the traces of edges of the cutting tools left on the wood material samples.

Samples made of fine-grained pinewood of longitudinal grain direction and of medium density fibreboard (MDF) [15,16] with dimensions of $18 \times 40 \times 500\,\text{mm}^3$ were used in the tests. Moisture of the samples used in the tests was less than 12%. The samples made of wood materials were milled at a speed (V_c) of 17, 31, 45 and/or 59 m/s. The fixed depth of cut adopted for all of the tests was 10 mm.

The traverse-longitudinal milling was performed with the use of the 1100-2 cutterhead [17] with a cutting diameter of 125 mm and nominally four cutting blades, with an adjustable projection of blades from the body. The regular projection of blades from the cutterhead body (C_r) is 1.6 mm. When testing the effect of the projection of blades on kickback speed, apart from the normal projection, a projection reduced to 0.8 mm was applied.

When testing the effect of the number of cutting blades, a standard 1100-2 head and a modified head with two active blades (the other two were inserted into the head body) were used (see Figure 5).

In the 1100-2 cutterhead the angular position of the blades with respect to the body is determined precisely, therefore, the rake angle cannot be changed. However, it is possible to prepare blades with different nose angles of the edge so as to change the clearance angle of the tool edges.

Apart from standard blades with a clearance angle of 12.5° and a nose angle of 52.5°, two sets of ground blades were also used: with a clearance angle of 5° and a nose angle of 60° and with a clearance angle of 25° and a nose angle of 40°, respectively.

All tests were performed at an air temperature of 20 ± 2 °C and a humidity of 40 ± 10%.

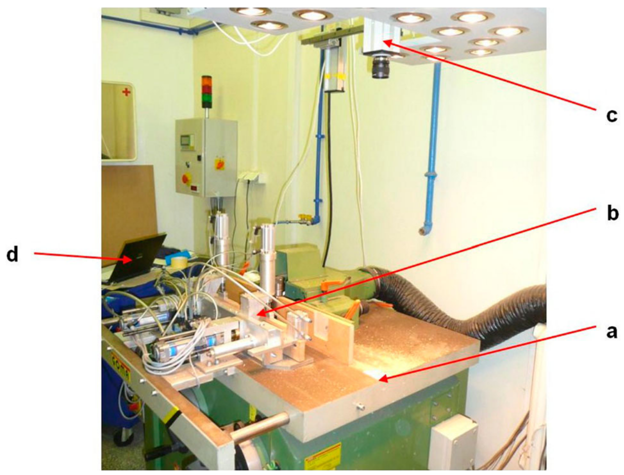

Figure 1. Kickback test stand.
Note: a = vertical spindle moulding machine; b = pressure unit; c = high-speed camera; d = camera control computer.

3. Results and discussion

3.1. *Effect of projection of blade cutting edges*

Results of the tests performed when milling pinewood at four milling speeds are presented in Figure 2. The diagram

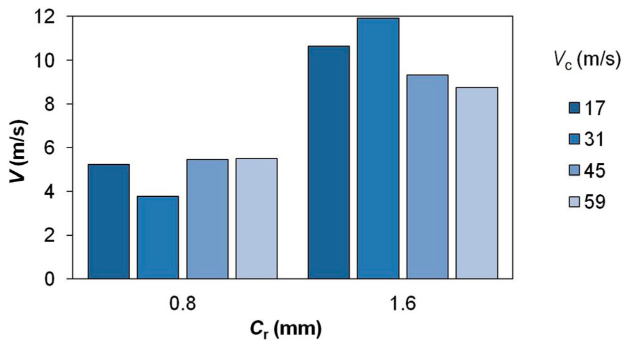

Figure 2. Kickback speed depending on the cutting edge projection during milling pinewood.
Note: C_r = regular projection of blades from cutterhead body; V = kickback speed; V_c = cutting speed.

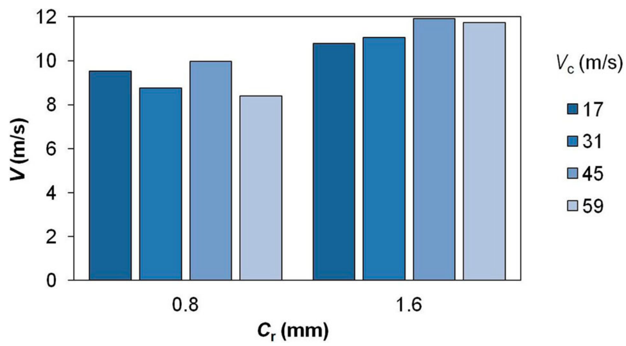

Figure 3. Kickback speed depending on the cutting edge projection during milling medium density fibreboard.
Note: C_r = regular projection of blades from cutterhead body; V = kickback speed; V_c = cutting speed.

shows a clear difference between the results obtained when milling with a small projection of cutting edges (4–6 m/s) and the results for regular projection (8–12 m/s).

Regardless of the blade setup, it is hard to notice any significant relation between the kickback speed and the milling speed.

The results of tests during the process of milling MDF samples are illustrated in Figure 3, where it is also possible to notice clearly smaller kickback speeds for the same milling speeds, recorded at a small projection of the cutting edges as compared to the kickback speed at regular projection.

In such a case there is also no relation between the kickback speed and the milling speed, both at small as well as at regular projection of blade cutting edges outside the cutterhead body.

The results of the analysis of variance regarding the experimental data matrix being the results of the tests of the speed of ejection of samples milled in two setup variants (with small and regular projection of blade cutting edges), with the use of four different milling speeds, are presented in Table 1 (pinewood samples) and Table 2 (MDF samples). These tables also include estimated values η^2.

Table 1. Analysis of variance relating to kickback speed observed during milling of pinewood at different speeds, with 1100-2 cutterheads with small and regular projection of blade cutting edges.

	One-dimensional statistical tests of variation significance Sigma-restricted parametrisation Effective hypothesis decomposition					
Effect	*SS*	*df*	*MS*	*F*	*p*	η^2
Absolute term	4623.636	1	4623.636	992.356	<0.001	–
Projection of cutting knives	537.858	1	537.858	115.439	<0.001	56.618
Cutting speed	6.876	3	2.292	0.492	0.689	–
Cutting speed × projection of cutting knives	69.785	3	23.262	4.993	0.003	7.346
Error	335.466	72	4.659	–	–	35.313

Note: Total number of tests: $N = 80$. Values significant at $p < 0.05$.

Table 2. Analysis of variance relating to kickback speed observed during milling of medium density fibreboard at different speeds, with 1100-2 cutterheads with small and regular cutting edge projection.

	One-dimensional statistical tests of variation significance Sigma-restricted parametrisation Effective hypothesis decomposition					
Effect	*SS*	*df*	*MS*	*F*	*p*	η^2
Absolute term	8471.140	1	8471.140	20876.488	<0.001	–
Projection of cutting knives	97.770	1	97.770	240.948	<0.001	64.761
Cutting speed	11.962	3	3.987	9.827	<0.001	7.923
Cutting speed × projection of cutting knives	12.022	3	4.007	9.876	<0.001	7.963
Error	29.216	72	0.401	–	–	19.352

Note: Total number of tests: $N = 80$. Values significant at $p < 0.05$.

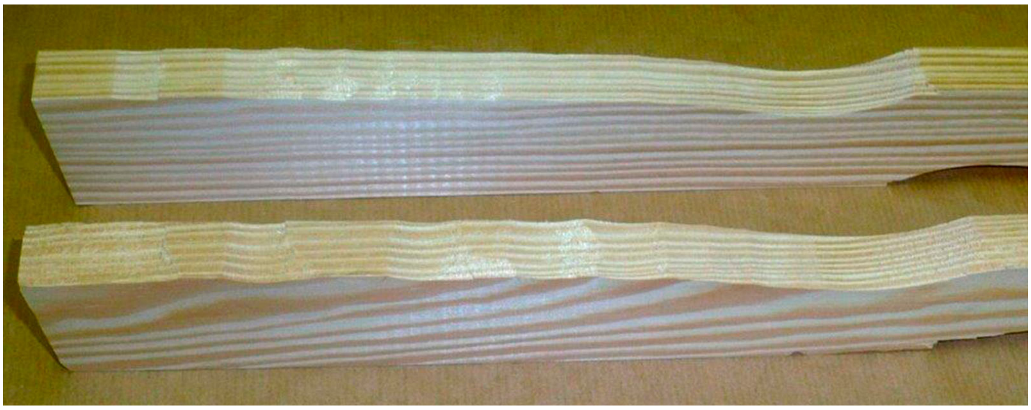

Figure 4. Pinewood samples milled at a speed of 17 m/s with a blade projection of 0.8 mm (upper sample) and 1.6 mm (lower sample).

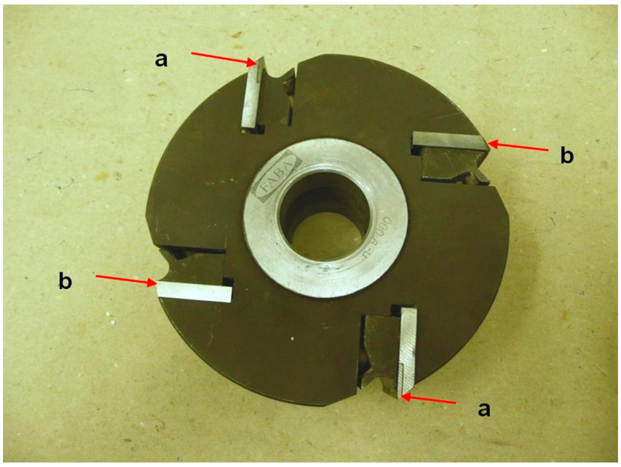

Figure 5. Modified cutterhead.
Note: a = active blades; b = blades inserted into the body.

These results clearly indicate that, in the case of pinewood milling, there is a strong effect of cutting edge projection (η^2 = approximately 57%) and little effect (<1%) of the cutting speed. A slightly greater strength of effect (>7%) is demonstrated by the interaction of these two factors.

In the case of MDF milling, the results obtained indicate also a strong effect of cutting edge projection (η^2 = approximately 65%) and little strength of the effect of almost 8% both for the cutting speed and the interaction of both independent factors.

The appearance of samples after kickback tests (Figure 4) milled at a speed of 17 m/s with 1100-2 heads with regular projection and those with reduced projection of blades differs significantly. The traces of blade impacts are considerably clearer (longer and deeper) in the case of the former. When comparing the appearance of the pinewood samples used in this experiment, it can be noticed that the number of traces of the tool edges visible on their surface is greater at cutting edge projection reduced to 0.8 mm than at regular projection of 1.6 mm (Tables 1 and 2).

3.2. *Effect of the cutterhead blade number*

The next experiment was to investigate whether and what number of cutting blades of the tool may affect the kickback speed.

A special, modified 1100-2 cutterhead (Figure 5) was prepared for this purpose, where two blades were inserted as much as possible into the body and ground so as not to be involved in the milling process.

Such a tool was used to test ejection during the process of pinewood and MDF milling to compare the results of these experiments with those obtained with the use of the non-modified four-blade 1100-2 head. Two extreme speeds of V_c = 17 and 59 m/s were applied during the tests.

It turned out that when using the two-blade head the observed kickback speeds of the pinewood samples were significantly smaller for both milling speeds, while in the case of MDF milling a lower kickback speed with the use of the two-blade head was observed only at the greater milling speed (Figure 6).

When machining the pinewood samples, a downward trend for changes in the kickback speed with an increase in the milling speed can be observed. In the case of the head with four active blades, the change is small, while in the case of the head with two blades the kickback speed drops to almost 0.

Results of the analysis of variance regarding the experimental data matrix being the results of the tests of the speed of ejection of samples made of two materials (MDF, pinewood), milled with the 1100-2 head equipped with two or four blades at two different cutting speeds (17 and 59 m/s), are presented in Table 3, which includes also the estimated values of the relative strength of the effect of individual factors on kickback speed (η^2).

These results also indicate the effect of all of the experimental factors and their mutual interactions, except for the interaction between all three factors, i.e., the number of active blades, the cutting speed and the workpiece.

The values of the strength of the effect of the number of blades and material are similar (approximately 28

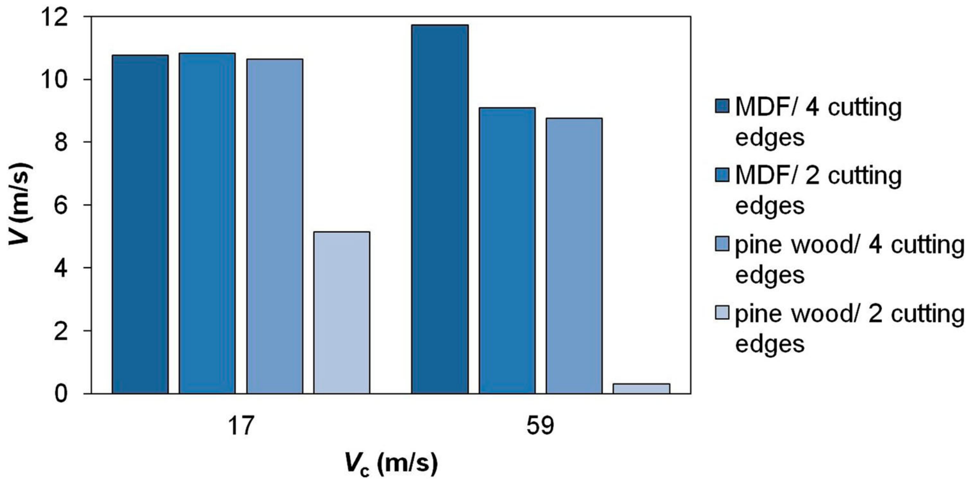

Figure 6. Kickback speed depending on the number of cutting edges.
Note: MDF = medium density fibreboard; V = kickback speed; V_c = cutting speed.

Table 3. Analysis of variance relating to kickback speed observed for different numbers of active blades.

	One-dimensional statistical tests of variation significance Sigma-restricted parametrisation Effective hypothesis decomposition					
Effect	*SS*	*df*	*MS*	*F*	*p*	η^2
Absolute term	5704.894	1	5704.894	1997.424	<0.001	–
Cutting speed	65.311	1	65.311	22.867	<0.001	5.188
Material	385.549	1	385.549	134.990	<0.001	30.625
Number of cutting knives	352.059	1	352.059	123.265	<0.001	27.965
Cutting speed × material	43.544	1	43.544	15.246	<0.001	3.459
Cutting speed × number of cutting knives	43.952	1	43.952	15.389	<0.001	3.491
Material × number of cutting knives	162.762	1	162.762	56.987	<0.001	12.928
Cutting speed × material × number of cutting knives	0.125	1	0.125	0.044	0.835	–
Error	205.641	72	2.856	–	–	16.334

Note: Total number of tests: $N = 80$. Values significant at $p < 0.05$.

and 31%, respectively) and their interaction is approximately 13%. The strengths of the effect of the cutting speed (approximately 5%) and other interactions are considerably smaller (Figure 7).

When comparing the process of milling with two-blade and four-blade heads at the same cutting speeds, it can be stated that at similar energy of a single blade impact, the number of these impacts within the specified time range might be even two times less in the case of the two-blade head, while the resistance to motion and the operation of friction forces are similar in both cases.

The interval between subsequent blade impacts becomes two times longer, thus slowing down sample ejection if the two-blade head is used. This phenomenon can be confirmed by comparing pinewood samples after kickback tests (Figure 8).

Paradoxically, a considerably greater number of traces of blade impacts appears exactly on the samples milled with a two-blade head (they can be seen particularly on samples milled at low speed), since the movement of the samples through the cutting tool (kickback speed) is much smaller. This leads to an additional effect of clearly visible overlapping of traces, which in turns leads to the reduced number of force impulses transferred to the sample by the blades.

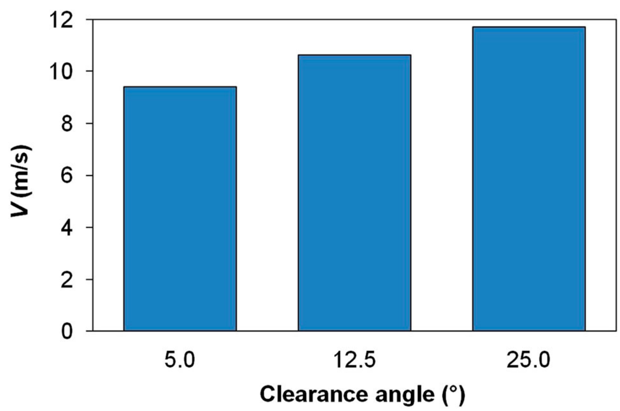

Figure 7. Average kickback speeds observed for different numbers of active blades.
Note: Total number of tests: $N = 80$. V = kickback speed.

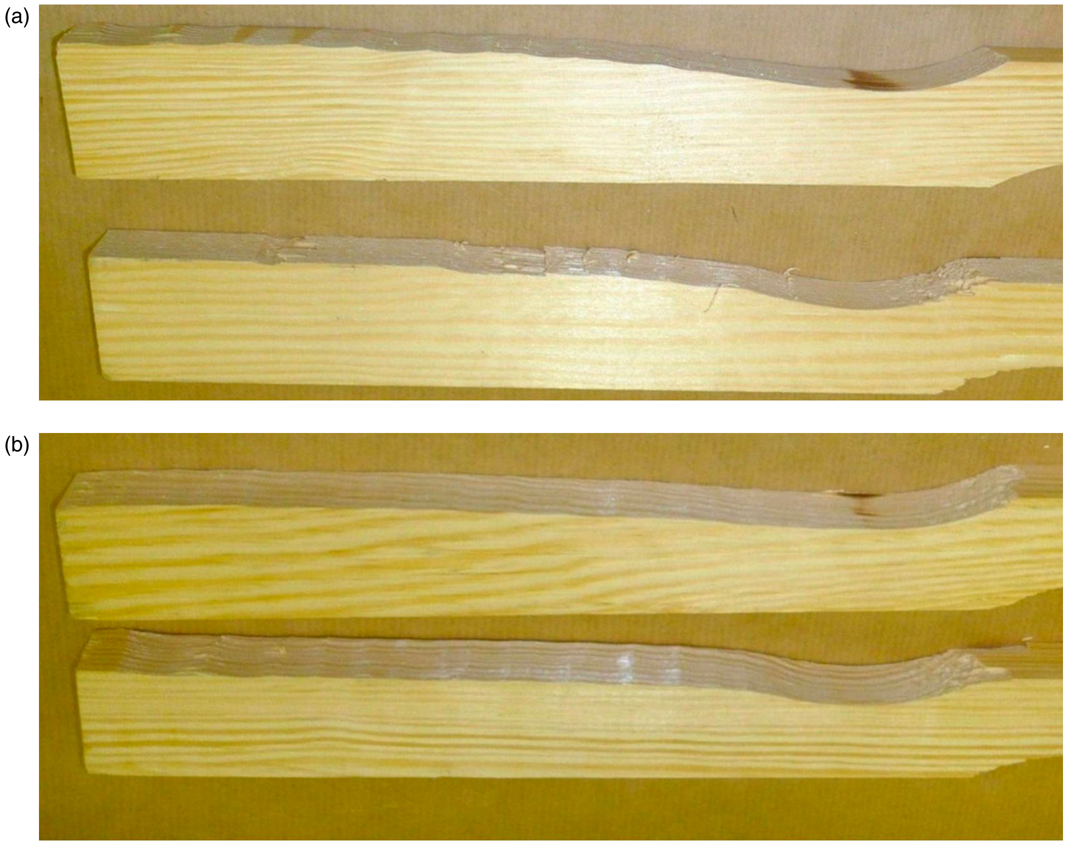

Figure 8. Pinewood samples after kickback tests using heads with different numbers of active blades: (a) four-blade head, milling speed 59 m/s (top) and 17 m/s (bottom); (b) two-blade head, milling speed 59 m/s (top) and 17 m/s (bottom).

This effect is so clear in the case of pinewood samples since the cutting resistances of this material are smaller. In the case of MDF, greater force impulses (resulting from greater specific cutting resistance) weaken the effect of doubling the time which elapses between subsequent blade impacts.

3.3. *Effect of clearance angle*

The 1100-2 cutterhead with ground blades was used in the tests to obtain different clearance angles (at a fixed rack angle). The projection of blades from the cutterhead body was the same in each case, i.e., 1.6 mm. The pinewood samples were milled with the heads at the following speeds: 17, 31 and 45 m/s.

Test results averaged for the three cutting speeds applied are presented in Figure 9. They indicate that the lower the clearance angle, the smaller the kickback speed.

Results of statistical analysis of the study results are presented in Table 4. They indicate a statistical significance of the effect of the clearance angle of the cutterhead blades on average kickback speed, and the force of this effect (η^2) is approximately 18%. The analysis results fail to confirm the effect of the cutting speed, while the highest experimental effect, of over 32%, is manifested by the

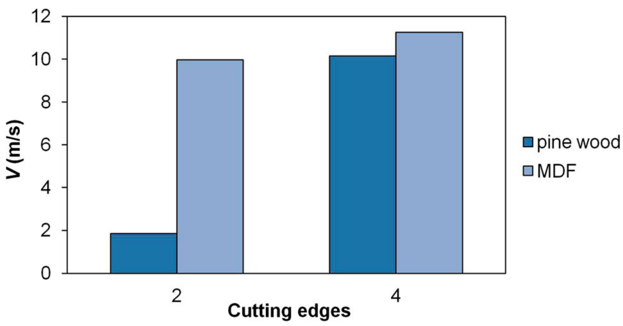

Figure 9. Average kickback speeds during milling of pinewood observed for different clearance angles.
Note: Total number of tests: $N = 90$. MDF = medium density fibreboard; V = kickback speed.

interaction between the cutting speed and the clearance angle.

In the appearance of the traces of blades on the surface of the samples presented in Figure 10, a slightly smoother shape of these traces can be noticed at the small clearance angle (5°), while at the large angle (25°), particularly for smaller cutting speeds, the traces of material chipping are clearly visible.

The results of statistical analyses of the effect of the clearance angles should be supplemented with theoretical

Table 4. Analysis of variance relating to kickback speed observed during milling of pinewood for three different clearance angles.

	One-dimensional statistical tests of variation significance Sigma-restricted parametrisation Effective hypothesis decomposition					
Effect	*SS*	*df*	*MS*	*F*	*p*	η^2
Absolute term	10072.060	1	10072.060	3900.479	<0.001	–
Clearance angle	78.292	2	39.147	15.160	<0.001	18.376
Cutting speed	5.494	2	2.746	1.064	0.350	–
Clearance angle × cutting speed	138.516	4	34.629	13.410	<0.001	32.515
Error	209.163	81	2.582	–	–	49.095

Note: Total number of tests: $N = 90$. Values significant at $p < 0.05$.

(a)

(b)

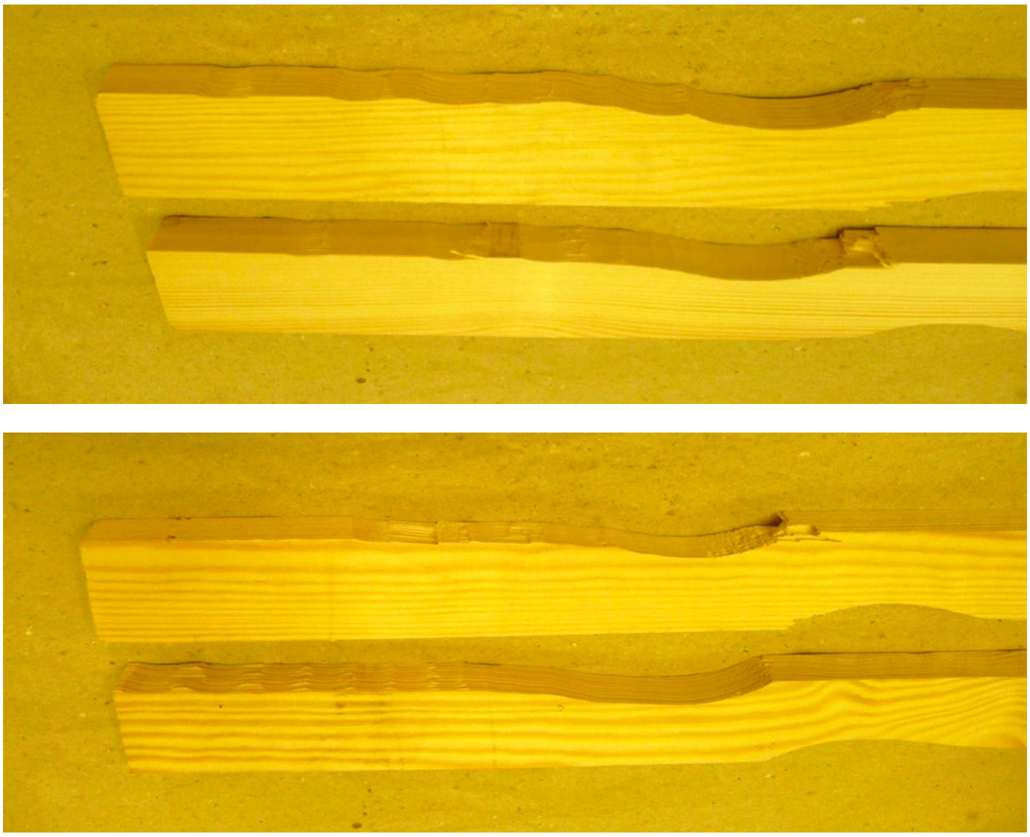

Figure 10. Pinewood samples after kickback tests using cutterheads with different clearance angles: (a) clearance angle small (5°), milling speed 17 m/s (top) and 45 m/s (bottom); (b) clearance angle large (25°), milling speed 17 m/s (top) and 45 m/s (bottom).

analysis. If we look at the moment of contact of the blade edge with the surface of the milled materials, it can be clearly noticed that at least two significant differences may affect the test results achieved.

The first of these involves the difference in the nose angles of the cutting edges, and the second involves the difference in the slope of bisectors of those angles to the material surface. If the clearance angle is small, the nose angle of the edge is 60° and the slope is 35°, while if the clearance angle is large, these values are 40° and 45°, respectively.

Both of these differences reduce the average kickback speed during the process of milling with a tool with a smaller clearance angle.

The first of them affects the density of the impact energy flow which is used to determine the ratio of the reduced impact energy to the cube of the reduced radius of curvature of the contact area of colliding bodies [18].

If the nose angle of the cutting edge is larger, at the same values of the reduced impact energy, the contact area and its reduced radius of curvature will be greater, therefore, the density of the impact energy flow will be smaller.

In this case, the yield point will be exceeded later and the part of the reduced impact energy converted to the cutting work will be smaller.

As a result of the latter difference, the direction of cutting force application in both cases is different. If the nose angle of the edge is larger and the clearance angle is smaller, then the component of this force, perpendicular to the material surface, thus responsible for the blade sinking into the material, is also smaller.

At small cutting speeds this component is even smaller, and the duration of the impact increases at the same time. This may result in partial indentation and sliding of the blade on the material surface, instead of cutting. The additional differentiating factor is the dynamic yield point of the material, the value of which depends on the impact speed (to be more precise – on the deformation speed) [18].

This also explains why at higher cutting speeds those differences do not affect the test results. As a result of shorter time and greater impact energy, the milled material will not manage to be removed from the guides by the cutting tools, but it yields and the cutting takes place.

A similar issue can be faced during the safety tests of ejection-preventing devices in wood planing machines performed for the purposes of product conformity assessment. The safety requirements specified in Standard No. ISO DIS 19085-7:2016 [19] include, among others, the precisely defined angle between the upper surface of the workpiece and the axis of the ejection-preventing pawl (connecting its rotation axis with the top), which should be at least 55°. As part of the aforementioned tests, the operation of the pawls is tested also by performing the test described in Standard No. ISO DIS 19085-7:2016 during which the pawls are inserted under the edges and then an attempt is made to remove the workpiece again. The results of these tests for different structural solutions of pawl devices used by the manufacturers confirmed that if the aforementioned condition of the angular position of the pawls relative to the workpiece was not met, they did not operate effectively. In such a case, new sharp pawls could not stop the reverse movement of the workpiece, even if its surface was coarse – after sawing (planed beechwood is normally used in tests).

Of course, even at the smallest cutting speeds applied during the tests, the dynamics of the cutting process and the forces applied are considerably greater than during the tests performed on pawl devices of the planing machines. So, it is impossible to simply compare the angles from the kickback tests with the angle determined in Standard No. ISO DIS 19085-7:2016 regarding the planing machines. However, in both cases it is the large angle between them that drives the edge into the material – otherwise, the edge slides on the surface of the material.

4. Conclusions

The results of the experimental tests presented in this article and the performed statistical analysis, as well as the conclusions drawn on the basis of the visual inspection of the traces left by the cutting edges on the surface of the milled samples, allow one to formulate several conclusions regarding the effect of the cutterhead setup or its modification which can be made by the user for the possible improvement of occupational safety in furniture making during operation of hand-fed vertical spindle moulding machines as manifested by smaller average kickback speeds during the experiments performed.

A measurable decrease in average kickback speeds, and therefore a possible improvement in occupational safety, resulted in particular from the reduced projection of blades from the cutterhead.

There is no doubt that it is therefore fundamental to use a cutterhead with a cylindrical body with as little projection of the cutting edges of the tool as possible for technological reasons.

Smaller kickback speeds were also observed with the smaller number of cutterhead cutting blades and with the reduced clearance angle of the cutting blades attached in the cutterhead. However, it is impossible to recommend reduction in the number of blades or the clearance angle, since this could have an adverse effect on the work quality and output.

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