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INFLUENCE OF CUTTING CONDITIONS ON KICKBACK SPEED IN MILLING WOOD MATERIALS

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ABSTRACT

An analysis of accidents has shown that many fatal and serious accidents during woodworking result from kickback. This study assessed the influence of cutting conditions on hazards associated with kickback in milling wood materials. The research concerned the severity of hazards but not the probability of kickback. The speed of kickback was accepted as the quantitative measure of these hazards. An original method of kickback experimental testing on unique research test stand was applied. The speed of kickback was measured in different cutting conditions. The experiment involved controlled changes in cutting conditions, such as the type of cutting tool, cutting speed, machined material, and tool wear. Statistical analysis of the results verified some common opinions and ideas on the impact of basic cutting conditions on the hazards resulting from kickback during milling of wood materials. In some cases, the results of empirical testing did not confirm the commonplace opinions.

KEYWORDS: Kickback, woodworking, mechanical hazards, accident, occupational safety.

INTRODUCTION

Operators of machines for working wood or wood-based materials are exposed to a considerable number of harmful factors (Kvietková et al. 2015, Rogoziński et al. 2015, Marchi 2017), but kickback of a workpiece is one of the main hazards associated with their work. For that reason, important international documents (ILO 2011, Directive 2006/42/EC, EC 2010) point out that "where the machinery is likely to be used in conditions involving the risk of ejection of workpieces or parts of them, it must be designed, constructed, or equipped in such a way as to prevent such ejection, or, if this is not possible, so that the ejection does not engender risks for the operator and/or exposed persons."

The guidebook definition (HSE 1998) describes kickback as dangerous and commonly occurring in hand-fed woodworking machines, especially in circular sawing machines, vertical moulding machines and planing machines. Kickback is also the most dangerous cause of accidents during operation of chainsaws, and the majority of accidents caused by kickback results from improper holding and handling of the chainsaw (Koehler et al. 2004).

The number of severe and fatal accidents during manufacture of furniture and in wood processing operations remains significant. For example, a total of 108 such accidents were recorded in Poland in the years 2011 to 2012 (GUS 2012, 2013). Analyses of accidents in wood processing (Dąbrowski 2003, Frank et al. 2010) indicate that in numerous cases, the workpiece suddenly ejected from underneath the operator's hands, resulting in a loss of balance. This leads to serious cuts of fingers and hands, which are the most common injuries from those accidents.

The analysis prepared by Chowdhury and Paul (2011) showed that the operator`s hand was pulled into the saw in over 65% of the cases in which the stock kicked back or jumped.

As many as three out of four severe and fatal accidents with woodworking machines for which courts have requested opinion from the Central Institute for Labour Protection in recent years were caused by kickback in multiple-blade circular saws, whereas one of the five severe accidents took place at a vertical moulding machine and also resulted from kickback.

It is commonly assumed that cutting conditions related to the design of the cutting tool, cutting parameters, and the characteristics of a workpiece influence kickback speed and thus the hazard to life and health of machine operators. However, it should be clearly stressed that the problem has not been sufficiently researched.

The possibilities of limiting the risk of kickback were seen by Trivin (1975), mostly in using cutting tools with design restricting the feed peer tooth. According to the British Standard (BS 6854 1989), the reasoning behind Limited Cutter Projection Tooling (LCPT) is, apart from increase in possibility of damaging the tool with high cutter projection and the severity of potential injuries suffered due to contact with such a tool, also a higher probability of occurrence and "aggressiveness" of kickback. The impact of the shape of chain links in portable hand-held chainsaws on limitation of excessive cutting resistance and the risk of kickback has been confirmed (Więsik 1992, Górski 1996). Although the standard EN 847-1 (1997) and its later edition formulate the requirements concerning the cylindrical shape of the tool body for hand-fed moulding and planing machines as well as the dimensions of chip flutes and cutter projection, it does not provide any justification for those requirements.

The condition of wear of the tools may also have a significant impact. According to the OSHA guidebook (1999), "a blade that is not sharpened, or that is set at an incorrect height, can cause kickbacks". This seems logical because numerous experiments confirm that increased wear of the cutting edges results in increased cutting force on solid wood (Kivimaa 1950) and MDF (Stewart 1988). There is a positive correlation between the wear of the cutting edge and specific cutting energy (Orlicz 1988).

However, little is known about the impact of cutting speed on kickback speed; according to the standard EN 848-1 (2007) on vertical moulding machines, cutting speeds below 40 $m \cdot s^{-1}$ increases the risk of occurrence of kickback.

It is generally assumed that the workpiece material also has a significant influence on kickback, for instance knots and natural changes in the direction of the grain in solid wood (HSE 1998). Apart from natural defects, solid wood contains foreign bodies (Andrzejewska -Jabłońska

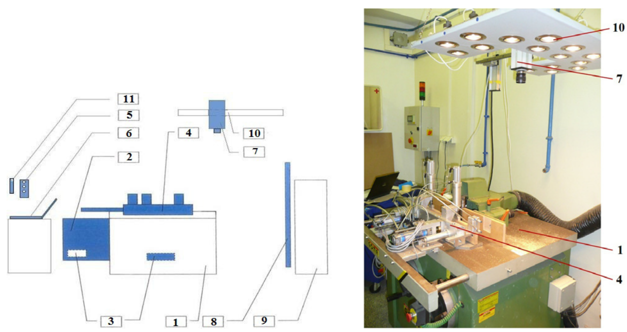
2011) that may cause damage to the cutting parts of machines and devices. According to Cooke and Blumenstock (1979), hard wood has a greater mass to volume ratio than soft wood. For that reason, it bears greater specific cutting energy while employees working hard wood are exposed to greater kickbacks. Similarly, Holcroft and Punnett (2009) claim that greater risks during woodworking are present in sawmills due to larger, heavier parts of the worked wood and greater mechanical energy related to sawmill machines.

After analyzing the literature, it was acknowledged that new systematic experimental research of the impact of the broadly defined cutting conditions (covering design of the cutting tool and its wear condition, cutting speed and machined material) on kickback speed are simply necessary, as only on that basis is it possible to formulate entirely reliable conclusions concerning occupational safety during milling of wood materials.

MATERIALS AND METHOD

Research test stand and method

The test stand for kickback tests was constructed based on the assumptions of EN 847-1 (1997). According to German standards BGR 500 (2008), the BG-TEST marking on tools for woodworking means that they passed the kickback test examination. Poland has not introduced obligatory certification of cutting tools; however, the test stands created at the Central Institute for Labour Protection – National Research Institute was used for extensive experimental research. The test stand used in this work is shown on Fig. 1a (scheme) and Fig. 1b.



(a) (b)

Fig. 1: Test stand: 1) moulding machine;2) machine control panel; 3) encoder with display; 4) unit for loading, pressing, and feeding of samples during their milling; 5) manipulator of the unit; 6) recording computer;7) high speed camera; 8) bumper plate; 9) chip and dust extraction; 10) lighting; 11) camera trigger.

The main parts of the test stand (Fig. 1) include a vertical moulding machine with stepless speed control and remotely-controlled pneumatic and mechanical unit for loading, pressing, and feeding of samples of wood materials during their milling. This unit contains a pneumatic cylinder for pushing samples in order to initiate kickback. The test stand was adapted for samples with standard dimensions of 18 × 40 × 500 mm.

Kickback speed was measured using a Fastec InLine 1000 high speed camera, which recorded the course of each test with the speed of 250 frames per second. Operation of the camera and analysis of recordings were performed using FIMS (Fastec Imaging, San Diego, CA, USA) and MiDAS Player (Xcitex Incorporated, Cambrige, MA, USA) software (Fig. 2). The applied solutions ensured high repeatability of testing conditions and precise measurement of kickback speed (the maximum relative measurement error did not exceed 1.5%).

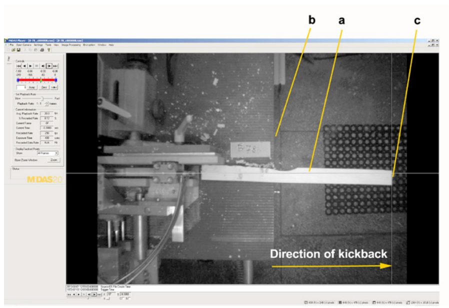


Fig. 2: Frame in MiDAS Player software: a) sample; b) edge of the test stand's table; c) cross hair.

The experimental procedure developed based on the guidelines of the EN-847-1 (1997) standard was modified in such a manner that kickback speed was determined as an average of 10 repetitions of kickback tests for specific cutting conditions.

All tests were conducted during stopped straight milling on a conventional vertical moulding machine without a mechanized feed. The speed of kickback of the workpiece was measured in different cutting conditions. The experiment involved controlled changes in basic factors (cutting conditions, which were the independent variables), such as the type of cutting tool, machined material, cutting speed and tool wear.

Multi-factorial analysis of variance was applied to the results of individual experiments.

It showed statistically significance factors and their interactions. The experimental effect size η^2 was also determined. Tukey's HSD post-hoc test was applied to compare pairs of intermediate speeds of kickback, which were observed for different levels of individual factors.

Cutting tools and knives

Two milling tools produced by FABA (Baboszewo, Poland) were used for testing the influence of cutting tool type, milling speed, and machined material on kickback speed (Fig. 3). Both tools had the same cutting diameters (125 mm) and were equipped with 4 cutting edges.

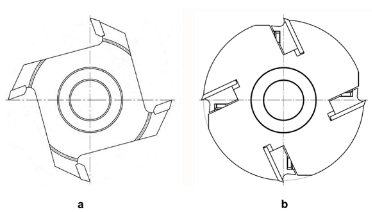


Fig. 3: Types of cutting tools: a) a one piece tool 3110 (NRF-not round form tool); b) a complex tool 1100-2 (RF-round form tool).

The influence of cutting tool wear on kickback speed was tested using a complex tool body 1100-2 (RF-round form tool) with replaceable cutting knives. Three sets of cutting knives, with different degree of wear due to milling of an 18 mm - thick chipboard, were used. The condition of individual edges was determined based on measurement of the standard wear parameter as observed in the bevel plane (VB_{Bmax} as per ISO 8688-2 (1996)). The results of those measurements are provided in Tab. 1.

Tab. 1: Tool wear characteristics.

Knife number	VB_{Bmax} - Maximum flank wear land width (mm)		
	Sharp knives	Slightly blunted knives	Blunt knives
1	< 0.020	0.887	1.495
2	< 0.020	0.846	1.355
3	< 0.020	0.805	1.400
4	< 0.020	0.829	1.401
Average value	< 0.020	0.842	1.413

Wood materials and cutting speeds

The tests were applied to samples of pinewood, MDF (EN 622-1 2003, EN 622-5 2006), and chipboard (EN 312 2003) with dimensions of 18 × 40 × 500 mm. The moisture content of the samples used in tests was approximately 10%.

Milling was generally performed at the speed of 17, 31, and 45 $m \cdot s^{-1}$, or additionally 59 $m \cdot s^{-1}$ when testing the influence of cutting tool wear on kickback speed was examined.

RESULTS AND DISCUSSION

Influence of the type of tool, cutting speed, and machined material

The results of tests using factory-sharp tools are presented in the diagram (Fig. 4). Influence of the cutting speed is particularly visible in the case of the NRF tool. Kickback speed increased if the cutting speed of all wood materials also increased. In the case of using the RF tool, it was not possible to observe distinct differences in the attainable kickback speeds depending on the cutting speed and the type of wood material. The aforementioned experiment results are fully consistent with both Trivin's (1975) and Więsik's (1992) views - the shape of the tool that limits the maximum thickness of the machined layer is far safer.

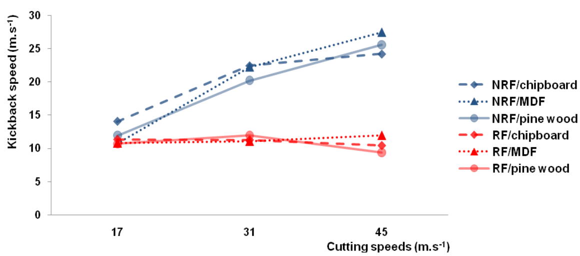


Fig. 4: Kickback speed depending on the type of cutting tool, machined material and cutting speed.

With the smallest milling speed, the results for both tools were very similar, irrespective of machined material. The variance analysis (Tab. 2) indicated statistical significance of the impact of all experimental factors present in the test, and of most interactions between them, on kickback speed.

Tab. 2: Analysis of variance relating to kickback speed observed during the milling of pinewood, MDF, and chipboard at three different cutting speeds of the NRF tool and RF tool.

Effect	One-dimensional statistical tests of variation significance Sigma-restricted parameterization Effective hypothesis decomposition					
	Sum of the squares	Degrees of freedom	Mean square	F-distribution	Probability	η^2
Absolute term	42,732.24	1	42,732.24	20,453.76	< 0.05	
Tool type	3,554.76	1	3,554.76	1,701.48	< 0.05	51.05
Cutting speed	1,407.79	2	703.90	336.92	< 0.05	20.22
Material	21.61	2	10.80	5.17	< 0.05	0.31
Tool type*Cutting speed	1,484.17	2	742.08	355.20	< 0.05	21.31
Tool type* Material	2.66	2	1.33	0.64	0.53	-
Cutting speed *Material	96.43	4	24.11	11.54	< 0.05	1.38
Tool type*Cutting speed*Material	60.14	4	15.04	7.20	< 0.05	0.86
Error	338.45	162	2.09			4.86

Note: total number of tests N = 180

However, a comparison of actual influence of individual factors (estimated based on the value of the η^2 indicator) indicates that the type of tool was the significant factor. It actually explained over 51% of total kickback speed variance. In the case of material type, the analogously estimated influence indicator was only 0.3%. Detailed results of the post-hoc HSD Tukey test of significance of intergroup differences, performed in relation to individual pairs of milled materials, are presented in Tab. 3.

Tab. 3: Results of post-hoc test (Significant intergroup differences) for testing of influence of the milled material.

HSD Tukey test; variable: kickback speed Estimated probabilities for post-hoc tests Error: Intergroup MS = 2.0892, df = 162.00				
Sample Material		{1} 14.920	{2} 15.687	{3} 15.617
1	Pinewood		< 0.05	< 0.05
2	MDF	< 0.05		0.961957
3	Chipboard	< 0.05	0.961957	

Those differences were rather small and sometimes even statistically insignificant. This result was surprising, given a previous report that the specific cutting energy of an MDF board is usually ca. 40% larger than in the case of pinewood (Dąbrowski 2008). Thus, it was not possible to demonstrate a significance relationship between kickback speed and the specific cutting energy. This result is somewhat contradictory to the views of Cooke and Blumenstock (1979) or Holcroft and Punnett (2009). Naturally, this fact does not mean that the properties of the worked material, in particular any possible local heterogeneities of its structure (e.g., foreign bodies and even exceptionally massive knots) may not have a significant impact on the cutting forces, therefore increasing the very probability of kickback occurrence.

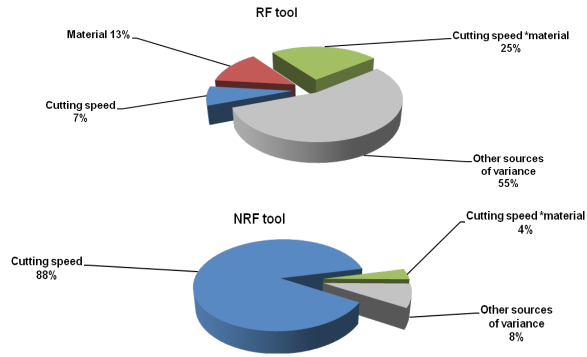


Fig. 5: Experimental effect size (η^2) of selected factors for kickback speed for two types of cutting tools.

More detailed statistical analysis of the results, conducted separately for each of the two types of tools, explicitly reveals the previously mentioned fact that the shape of the tool determines the nature (force) of the impact of cutting speed on kickback speed (Fig. 5).

Influence of tool wear

The results of testing of influence of tool wear on kickback speed during milling of pinewood are presented in Fig. 6. There was a distinct decrease in kickback speed in response to increased cutting tool wear.

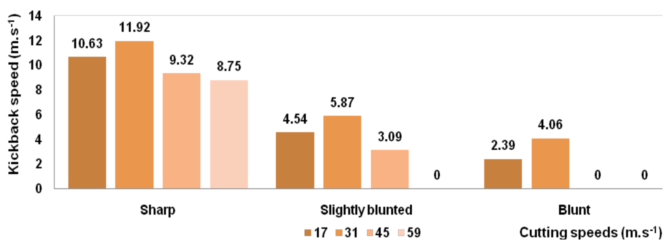


Fig. 6: Kickback speed in relation to tool wear during milling of pinewood at different cutting speed.

Detailed results of analysis of experimental data variances are presented in Tab. 4. All experimental factors and their interactions had a significant statistical impact on results of the experiment. However, the decisive factor impacting the result of the experiment was the condition of wear of the cutting edge; it accounted for approximately 58% of total kickback speed variance.

Tab. 4: Analysis of variance relating to kickback speed observed during milling of pinewood at different speeds using 1100 milling head with sharp, slightly blunted, and blunt cutting edges.

Effect	One-dimensional statistical tests of variation significance Sigma-restricted parameterization Effective hypothesis decomposition					
	Sum of the squares	Degrees of freedom	Mean square	F - distribution	Probability	η^2
Absolute term	3,334.329	1	3,334.329	675.0301	< 0.05	
Cutting speed	452.142	3	150.714	30.5118	< 0.05	17.73
Knife wear condition	1,480.285	2	740.142	149.8407	< 0.05	58.05
Cutting speed *Knife wear condition	83.932	6	13.989	2.8320	< 0.05	3.29
Error	533.469	108	4.940			20.92

Note: Total number of tests N = 180

Detailed comparisons of significant intergroup differences using the post-hoc HSD Tukey test performed in relation to the wear condition of the cutting knives confirmed the statistically significant difference between average kickback speed observed for sharp knives and average speeds for blunt knives or slightly blunted knives (Tab. 5).

Tab. 5: Results of post-hoc testing (Significant intergroup differences) for testing of the influence of tool wear.

HSD Tukey test; variable: kickback speed Estimated probabilities for post-hoc tests Error: Intergroup MS = 4.9395, df = 108.00				
Knives		{1} 10.195	{2} 3.3742	{3} 2.2442
1	Sharp		< 0.05	< 0.05
2	Slightly blunted	< 0.05		0.063947
3	Blunt	< 0.05	0.063947	

The influence of tool wear on kickback speed was mostly observed for higher speed of milling of pinewood samples, when kickback was completely slowed down and stopped.

Certainly, the dependencies discussed do not evidence that the use of sharp tools is, generally speaking, less safe than in the case of blunted ones. On the contrary, it may be assumed that in the case of milling with a tool with increasingly worn cutting edges, the probability of kickback is also increased (due to growth of cutting forces). Moreover, it is difficult to ignore the mundane fact that the wear of the cutting edges is unfavorable from the technological point of view (it reduces the quality of working).

CONCLUSIONS

The type of cutting tool had a very noticeable impact on kickback speed. In the case of a tool with non-cylindrical body shape, kickback speeds were definitely higher than in the case of tools with cylindrical body shapes. These results were confirmed especially for higher (approximately 30 or 40 $m \cdot s^{-1}$) cutting speeds.

Moreover, the results confirmed the commonly accepted views on the principles of correct selection (from OSH point of view) of tools for hand fed machines.

It was observed that the increasing a cutting speed of non-cylindrical body shape tool resulted in significant increasing the kickback speed. On other hand, in the case of a tool with cylindrical body shape, the change in cutting speed had practically no impact on observed kickback speed.

Experimental results showed completely different impact of cutting speed on kickback run if these two different types of tool were used.

During operation with factory-sharp tools, the impact of machined material on kickback speed was inconsiderable and sometimes even statistically insignificant. Therefore, the common opinion on high impact of that factor (especially on high significance of the specific cutting energy) was not confirmed in empirical tests. That does not in any way mean that knots or other defects which locally change specific cutting energy of machined material have no influence on risk of kickback.

A distinct decrease in kickback speed was also observed in response to increased cutting tools wear. This result indicated that though operation with significantly worn tools is obviously more risky, but kickback speed, i.e. hazard severity is then lowers than in case the use of sharp tools.

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