Global Forest Journal
Journal homepage: https://talenta.usu.ac.id/gfj

The effect of the feed rate and revolutions of the cutting tool on the amounts of created chips in dust and respirable sizes from milling particleboards, and medium-density fibreboards

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ARTICLE INFO
Article history:
Received: 20 June 2024
Revised: 11 July 2024
Accepted 18 July 2024
Available online 30 July 2024

E-ISSN: 3024-9309

How to cite:
M. Júda, T. Rogoziński, R. Kminiak, J. Šustek, "The effect of the feed rate and revolutions of the cutting tool on the amounts of created chips in dust and respirable sizes from milling particleboards, and medium-density fibreboards," *Global Forest Journal*, vol. 02, no. 02, July 2024.

http://doi.org/10.32734/gfj.v2i02.16735

ABSTRACT
In furniture manufacturing the finish-stage milling of wood-based materials creates chips in considerable amounts of dust and respirable sizes. Due to the limitations of dust-extracting equipment, the removal of chips is never perfect. Thus, small chips could escape the evacuation zone and pollute the surrounding air. A newer alternative method to solve this issue may be limiting the creation of those chips within a source. The presented article aimed to study the effect of technological variables on amounts of chips in dust and respirable sizes from medium-density fibreboards (MDF) and particleboards (PTCB). The materials were milled at a constant width of cut by 1mm, with the changing feed speed (vf) by 6, 8, 10, and 12 m•min-1, and with revolutions of the cutting tool (n) in the range of 16,000; 18,000; and 20,000 revs•min-1. In dust, we cover chips in the size range below <0.125 mm, and respirable size below <10.0 μm. The dust ranges from collected samples were estimated by sieve analysis with pre-defined mesh sizes by weighting the retained mass and with the laser analysis chips in respirable sizes were determined. The number of chips in the dust size ranged for MDF by 34.7-40.8 w % and in PTCB by 38.1-54.7 w%. Amount of chips in respirable size for MDF by 0.01-18 % and for PTCB by 0.01-4.5 %. Increasing (vf) from 6 to 12m/min significantly lowered amounts of Fine and respirable chips ($p<0.05$) in PTCB, no matter on an adjusted cutting tool (n). In MDF such effect was observed only with (n) 20,000 revs/min for respirable sizes.
Keyword: Average Chip Thickness, Laser analysis, Respirable size, Wood-based Materials, Wood Dust

1. Introduction

Usage of wood-based materials such as particleboards and medium-density fibreboards (MDF) is essential in furniture production and interior decoration [1]. Before finalising the workpiece to the required shape and dimensions materials must be multiple times processed, usually by mechanical work. During the mechanical processing (machining) with a specific method, a material is mechanically moulded into a required shape and dimensions during which a small thin layer of unwanted material called a chip (AmE particles) is created by an acting of the cutting tool (DIN 8589). Depending on the used method and used cutting tool this chip would have various shapes and sizes. When those materials are milled with a shank milling cutter on 5-axis CNC milling centers or routers chips usually have very small sizes, often in dust sizes. Typical woodworking activities that may produce chips in the dust sizes are sawing, routing, turning, milling [2]-[4], and especially finishing operations such as sanding [5]-[8]. The creation of such very small chips may be harmful to human health because those small chips can easily spread during the process to the surrounding environment (dust extraction is never perfect) and pollute the air, which occupants here may inhale directly [9]. The issues of the wood dust origin during wood or wood-based materials machining were studied and discussed by many authors [10]-[19] and many more studied the actual effect of exposure to wood dust on human health, i.e. (Alwis U., et. al. 1999 [20]-[30]. Here authors showed that the presence of wood dust in the surrounding work environment is heavily related to sinonasal symptoms, cavities, and other health-threatening issues and can cause non-reversible illnesses. From the point of definition of what wood dust is, a definition is not extensively described, but, from the point of the definition of dust, it covers all small particles in the size range of 1 to 400 μm [31]. However, no matter what the upper size range limit is, the most harmful are those of size <100 μm and especially below <10 μm [32]. A detailed description of a general particle size that can be breathed by the nose and their penetrating efficiency to terminal bronchioles into the gas-exchange region of the lungs defines ISO 7708 and EN 481 standards (respirable, thoracic, and inhalable).

Exposure to wood dust is dangerous not just for human health, but also from the perspective of equipment located in this environment. Wood dust is also a source of explosion [33]-[34], deteriorates manufacturing technology, damages modern mechanisms and circuits, and may disable modern optical systems of surveillance [35]. Thus, it must be removed. However, the removal of the dust is a hard task [36]. Despite the presence of modern exhaust systems, the occupational safety standards and limits for wood dust (NIOSH has set a recommended exposure level of 1 mg/m3 total dust) still indicate the mandatory use of masks or respirators with filters for all companies [37]. It is so because the only option how to remove dust is to be as close as possible to the zone of chip creation. The removing chip mass during cutting while the interaction of the cutting tool has a negative linear flow relation to the total air flow rate from the exhaust system [38]. Removed chips from the machining process have a higher speed from the momentum of the cutting tool as the tool cuts material and removes created chips from the workpiece, than the speed of airflow present in the exhaust system. This made the chip flow boundary and diffusion angle very difficult to estimate [10],[39]. The CNC milling center dust collector is difficult to manage compared to other older woodworking machinery. With a table saw, the dust is created in one fixed location and flung in one predictable direction while within a CNC machine, the cutter heads with the mounted cutting tool move in various directions even at the same time around the workplace (bed), as well as up or down simultaneously. Thus, the flow of chip mass is in all directions [36]. However, in the case of CNC machines, these issues are more relevant today, because they are often the cause of increased dust in the surrounding air after implementation to the manufacturing. There is no possibility of effective removal of dust particles that are dispersed in the air during CNC machining, especially when the tool moves considerably long distances in many directions because the dimensions of the workplace are large, which is in most cases of all CNC in furniture facilities [36],[40] and thus, alternative methods for solving these issues are welcoming.

In the available literature, some articles studied the operational parameters for the presence of airborne wood dust particles during sawing, milling, or drilling the wood and wood-based materials on more conventional devices [3],[19], but similar publications for collected chip mass are very rare and not extensively studied with properly adjusted machining conditions. However, today many companies in the furniture and joinery industry use computer numerical control (CNC) machines in their production line, where the workpiece is machined simultaneously multiple times. This is not possible with the use of older devices. During manufacturing, numerous parameters must be adjusted on the CNC machines for material processing. Typical is the frequency of the cutting tool, feed rates, the width of cut, the depth of cut, cutting tool parameters, etc. [41]-[42]. The wood chip size depends mainly on the machining process, which includes even the state of the cutting tool, the type of cutting process and its conditions, and especially operational parameters [43]-[49]. In most notable works [3], [19], [50]-[51] the authors studied operational variables on the airborne chips. They suggest that the most important factor in the amount of airborne wood dust during milling is the average chip thickness and the material structure. If such behavior is present for airborne chips, to some point in collected chip mass, this behavior also may be present. However, the milling conditions of wood-based materials compared to published studies are today much different. In manufacturing technology, the current trend of using cutting tools prefers to use a helix (spiral) shape, where each point of the helix acts like a single-point cutting tool. Helical teeth are usually preferred over straight teeth because the tooth is partially engaged with the workpiece as it rotates. Hence, the cutting force and the torque are lower, resulting in a smoother operation [42], [52]-[53].

Here, we tried to look at this topic from a different angle. If the sources of wood dust emissions are considered mechanical processes [18], [40], [54], thus the source must be in the processes associated with the creation, then molding, or shaping of the chips. To prove this statement, this paper aims to analyse created chips in dust sizes, estimated from collected chip mass which represents the very likely source of pollution. Due to the aim of the topic, we analysed the created chip mass from the modern finish milling process of wood-based material by using a helix design of a shank cutting tool, with the use of a CNC milling center. The emphasis is aimed at studying the change of percentual share (if is present) of dust-sized chips in the volume by varying operational parameters. In the presented experiment, the feed speeds, and revolutions of the cutting tool for the total amount of created dust-size chips from the process of milling medium-density fibreboard and particleboard were studied.

2. Method

For experiments, we bought two different but commercially available and certified particleboards (PTCB) and medium-density fibreboards (MDF) from Kronospan, Inc. Provided mechanical properties are shown in Table. 1. The medium-density fibreboard (EN 622-5) and particleboard (EN 312) were without any surface treatment, to remove contamination of samples from surface coating material. Delivered panels were in large dimensions, and for easier manipulation and fixation on the vacuum clamps, we crosscut the large plates on a circular table saw (FELDER K-500) into the form of smaller blocks, with dimensions of 500×300×18mm. Created edges were not treated, due to the possible contamination of the samples with sanding material. Those blocks were milled along the longest side by peripheral milling with climb milling direction (conventional milling).

Table 1. Main mechanical properties of samples

Name of parameter	Unit	PTCB	MDF
Length × Width × Thickness	mm	500×300×180	500×300×180
Density	$kg \cdot m^{-3}$	≅ 680	≅ 720
MOE	MPa	≅ 11	≅ 20
MOR	MPa	≅ 1,600	≅ 2,200

Designing such a setup of machining allowed us to simulate the finishing stage of the milling process, usually used on 5-axis CNC milling centers or routers in fully automatized manufacturing. The milling experiment was made with the use of the 5-axis CNC machining center SCM Tech Z5, designed for the timber industry and manufactured by SCM, Italy. The workplace of the CNC machine consists of 6 adjustable beam supports, equipped with vacuum clamps used for mounting and fixing the machined workpiece. Here, the tested workpieces were mounted on 2 vacuum clamps with the distance between them from the edges of the sample's edges 50 mm, equally placed to minimize the unevenly distributed effect of workpiece vibrations on distribution. For milling, we used a new spiral router (shank) milling cutter with three cutting flutes "blades". Such a tool has no new modernized design parts, to remove the effects from different angled cutting leaves, positive-negative cut compressing chips without chip flow, etc. on chip size distribution. The cutting tool was manufactured by ITA Tools, the main technical data given by the manufacturer are shown in Table. 2. Tool have been chosen to cover the widest population of used tools in CNC milling. A used shank milling cutter it's a commonly used cutting tool in modernized woodworking companies, due to its high tool lifetime and lower cost. The tool was mounted in the HSK F63 tool holder in the experiment without diameter reduction to eliminate the possible effect of slipping between reduction and tool or reduction and tool holder. Cutting edges were resharpened two times due to the expected tool lifetime to eliminate the tool wear effect as much as possible, based on the pre-described tool lifetime. No blunting or different forms of tool wear were measured before or after the experiment. Due to limited options on how to collect the chip mass in the airflow stream from the central dust-collecting device in the facility without contamination of samples with different materials and thus ensure its "cleanness", we built a custom extraction device system for chip collecting. Detailed setup is shown in Figure 1.

Table 2. Main technical data of cutting tool

Name of parameter	Unit	Value
Working diameter	mm	20
Working length	mm	120
The angle of the helix	°	30/60
Material	-	Solid carbide tool
Flutes	-	3
Chip flow	-	Upper-cut

The Presented system is based on the pre-existing extraction device (STILER FM470), custom-designed hood (a) which allowed us to collect chips as closest as possible near the cutting zone where the chip is created, and a custom-designed gathering box (b, c) with an attached filtration textile (HEPA textile type H13) inside (d). The created chip mass from the milling process is sucked by the air through a custom hood (a) and by air stream is created chip mass is conducted through PVC hosed by air from the extraction device to the attached filtration textile into the filtration box (c). The PVC hoses were of type PUR (EL DN110) antistatic with a surface resistance of 103 ohm and a coefficient of wear of 43 mm^3. By using such a designed device, we were able to collect chip particles whose lower collecting limit was based on a used filtration textile, which in our setup for HEPA grade of H13, is a 99.95 % collection of all particles in the airflow measuring 0.2 µm in diameter.

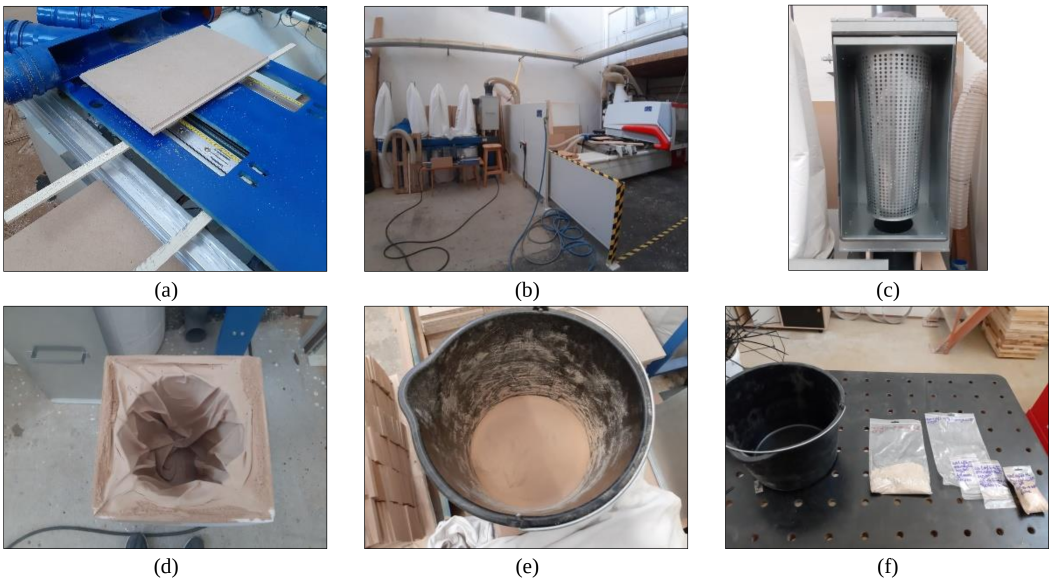

Figure 1. Methodology of samples gathering, where (a) – custom hood for chip mass collecting, (b) – extraction device, (c) – custom collecting box with a filtration textile, (d) – collected material samples, (e) – temporarily place for samples, (f) – stored samples in the PVC plastic bags

Detailed calculations showed based on weighting collected and removed mass on filtration textile that our setup achieved PTCB's lowest efficiency (99.3%), and MDF (98.2%). Thus, we believe our setup was sufficient for the presented experiment. Workpieces were milled until approximately 50±1 g of chip mass was collected. The whole volume of mass from the filtration textile was placed first into the PVC box (e) and later moved to the plastic bags (f), where samples were sealed and protected before the next analysing. After every mentioned step in sample collecting, every piece of acting equipment was cleaned with pressured air and surrounding air sucked by a vacuum cleaner for 5 min to remove all possible airborne particles from the surrounding environment to minimize falling of particles on the surface and polluting samples with the previous conditions.

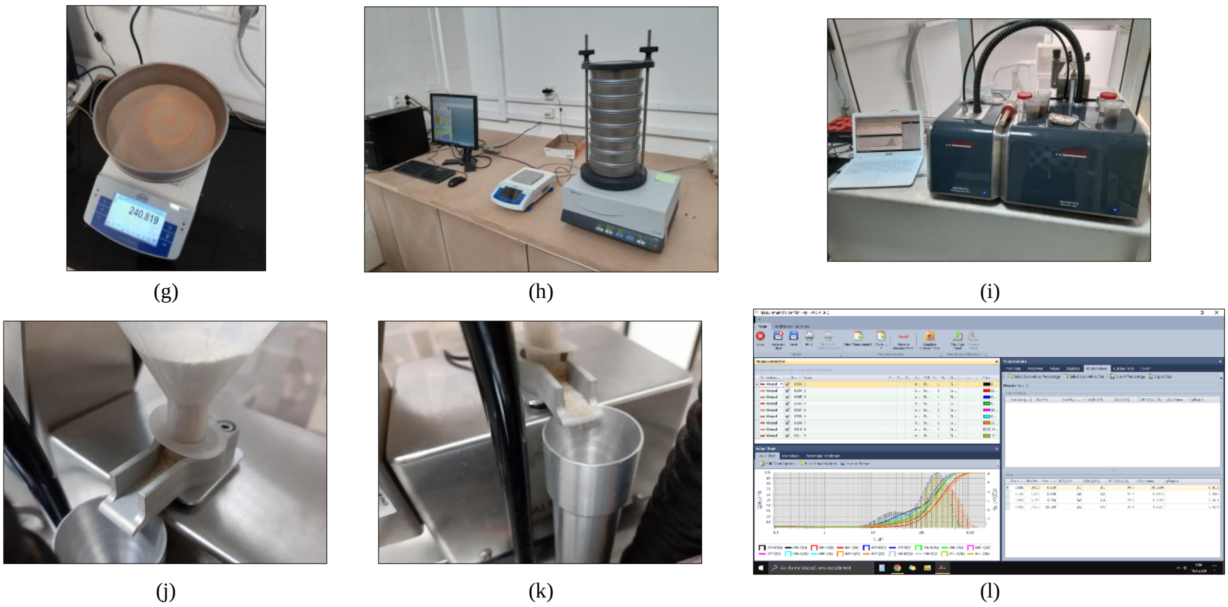

Figure 2. Methodology to obtaining the results from sieve analysis, where (g) – weighting the sieves with retained chip mass, (h) – set of sieves, and from laser analysis, where (i) – Fritsch Analysette 22, (j) – the vibrating feeder with mass, (k) – feeding the laser device with granular samples, (l) – results of laser analysis from MaScontrol

For the size analysis of chips, two methods were used to determine the sizes, sieving, and laser analysis. First, we used sieve analysis, where we used a pre-defined set of sieves with the mesh sizes in the size range interval of 2 mm, 1 mm, 0.500 mm, 0.250 mm, 0.125 mm, 0.063 mm, 0.032 mm, and the Pan (representing all sizes below <0.032 mm), stacked on each other. The stacked sieves were placed at the vibration stand of the screening device Retsch AS 200c (Retsch GmbH, Haan, Germany). Parameters of the sieving were in recommendations for wood dust from sanding [12]-[17], [57], due to pre-made measurements where the size distribution showed similar distribution from sanding with a high particle share in chips with sizes below <125µm [54]. The sieving was done with the sieve interruption frequency each f – 10 sec, network deflection frequency amplitude - 2 mm·g-1, total screening time τ = 15 min. The proportions of the remaining mass of fractions on the sieves after the sieving process were on an electric laboratory balance scale Radwag 510/C/2 (Radwag Balances and Scales, Radom, Poland) weighed with an accuracy of 0.001g. From weighing the retained mass on sieves, the percentual distribution was calculated. Due to size limits o f sieves, here we cover dust size even below <0.125 mm.

Due to limited options of sieving analysis, the content of chips in sizes <10.0 µm (based on the convention ISO 7708:1995 and definition of respirable sizes [55] all below <10.0-0.0 µm) were estimated with the use of laser analysis to specify details regarding the dust with the size of particles smaller than <0.250 mm due to insufficient found sum below lower sizes. A similar setup was used by authors [35], [43]-[44], [46], [47]-[49]. The laser particle sizer automatically measures a particle size according to a predetermined Standard Operating Procedure and theoretical assumptions. The results obtained were processed are controlled by MaScontrol software (Fritsch, Idar-Oberstein, Germany) working on the principle of "reverse Fourier optics" (ISO 13320-1). The results of laser analysis give two quantities: the sum of the Q(x) distribution and the q(x) density distribution. According to dQr(x) = qr(X) dx, qr(x) is a component of dQr(X), which is contained in the interval dx for particles from x and x + dx. The result is a random variable r (when r = 3, it means volume distribution; assuming a constant density of tested material, it is also mass distribution), where:

$$q_r(x) = \frac{x^r \times q_0(x)}{\sum_{i=1}^{n} x_i^r \times q_{0i}(x_i)} = \frac{dQ_r(x)}{dx} \quad (1)$$

From this volume the estimated percentual share of specific sizes of chips in sizes <10.0 µm was obtained. This distribution determines the mass share of the particles in the assumed size ranges of the dust chips collected in the volume of <0.250 mm chip mass by MaScontrol software. From laser analysis, we obtained 9 measurements for one combination. Because software estimated the percentual share from the analysed volume, to obtain values in the whole mass additional calculations were performed as follows:

$$c_i = c_{s250} \cdot cL_i \quad (2)$$

where:

ci: mass share of dust particles in the assumed size range of the entire mass of dust

cS250: mass share of dust collected during the sieve analysis in the sieve with mesh sizes <0.250 mm

cLi: mass shares of the dust in the assumed ranges determined by using laser diffraction analysis in the cS250 share.

Adjusting proper cutting conditions for milling operation depends on the machining stage, the required accuracy of final dimensions and final surface quality, the used cutting tool and its main design parameters, various additional parameters such as the adjusted optimal energy consumption, the final use, the price of work, and others. Studying all variables at the same time would be very complicated and not easily controllable in the presented experiment. To choose variables that are suitable for milling operations, it was focused on studying the main operational parameters of the milling process, which are directly adjustable and controllable from the point of a CNC machinist. Those variables are revolutions of the cutting tool, feed rate, and width of cut.

Table 3. Cutting conditions

Name of parameter	Unit	Value
Workpiece	-	Particleboard / Medium-density fibreboard
Machining	-	Milling, down-milling
Feed rate (vf)	$m \cdot min^{-1}$	6, 8, 10, and 12
Width of cut (ae)	mm	1
Revolutions of the cutting tool (n)	$revs \cdot min^{-1}$	16,000; 18,000; 20,000

Recommended revolutions are usually pre-described by the manufacturers of cutting tools, based on machined workpieces, but sometimes are even set by experience. Setting proper values of the width of the cut and feed rate, compared to revolutions of the cutting tool, is more complicated because it differs for every wood-based material in the finishing stage. Here we choose to machine the materials with a constant width of cut by 1mm and different feed rates and revolutions of the cutting tool (Table 3).

As mentioned earlier, the kinematic variable average chip thickness was shown to be the most significant factor for reducing airborne dust chips in the working environment. When peripheral cutting is conducted, the non-constant thickness of cut h is given. In this case, a comma-shaped chip is formed. Therefore, the notion of the average thickness of cut hm (average chip thickness) must be introduced [32]. Thus, due to the large variety of adjusted variables, we decided to simplify the results by introducing this variable to the experiment. The average chip thickness is an informative variable, which provides a large amount of information on the cutting process itself. It makes it possible to compare operations in which different cutting data and tools are used. This is because the average chip thickness indicates how much cutting is performed by each tooth of the tool [19]. The kinematic parameter of average chip thickness is based on the feed speed, the number of cuttings tooths (flutes) of the cutting tool, rotational speed, depth of cut or width of cut (depending on the tool orientation), and diameter of the tool according to (Koch P. 1964). The current publications [32] of wood sciences and technology describe its equation in the following form:

$$\mathrm{h_m} = \frac{f_z \cdot a_e \cdot 360°}{\pi \cdot \mathrm{D} \cdot \arccos\left(1 - \frac{2 \cdot a_e}{D}\right)} \cdot \sin\kappa \text{ in [mm]} \tag{3}$$

where:

fz: feed per tooth (chip load) in [mm]

ae: width of cut in [mm]

D: the tool's diameter in [mm]

κ: cutting edge angle in [°], here 90°

To support the hypothesis that changing feed rate and revolutions on the cutting tool affect fine and respirable size ranges, statistical calculations were made. Here a factor of significance ($p<0.05$) was calculated. Due to the normal distribution of data from sieve analysis, all variables such as material, feed speed (vf), and revolutions of the cutting tool (n) were subjected to the two-way analysis of variance (ANOVA) to determine the effect of individual variables on the size ranges. However, the data from laser analysis doesn't show the normal distribution, and thus medians were analysed by one-way ANOVA. In ANOVA calculations, we used a Shapiro-Wilks test with a 95 % confidence level to compare the mean values of variables and the Kruskal-Wallis's test to compare the median values. Statistical calculations were made by Statistica 12.0 (TIBCO).

3. Results and Discussion

Collected chip mass samples were by sieve analysis divided with the use of pre-defined sieves of different mesh sizes into size ranges, based on the used sieves. The base distributions (Figure 3-4) demonstrate the percentual weight share.

Cutting conditions	Workpiece		PTCB	PTCB	PTCB	PTCB	PTCB	PTCB	PTCB	PTCB	PTCB	PTCB	PTCB	PTCB
	Width of cut (ae) [mm]		1	1	1	1	1	1	1	1	1	1	1	1
	Feed rate (vf) [m/min]		6	8	10	12	6	8	10	12	6	8	10	12
	Revolutions (n) [revs/min]		16,000	16,000	16,000	16,000	18,000	18,000	18,000	18,000	20,000	20,000	20,000	20,000
Size ranges [mm]	>2.00-2.00	Coarse	0.02	0.02	0.03	0.05	0.03	0.01	0.09	0.08	0.06	0.08	0.05	0.03
	<2.00-1.00		2.52	2.79	2.84	2.56	2.95	3.10	3.17	3.34	2.26	1.94	2.37	2.65
	<1.00-0.500	Medium	17.61	18.83	19.41	20.52	18.36	21.22	21.99	24.65	16.16	18.13	20.66	22.50
	<0.500-0.250		34.67	37.44	39.07	39.69	38.45	39.87	39.91	40.81	38.11	39.64	40.79	39.74
	<0.250-0.125		31.61	30.22	29.42	28.55	31.20	28.17	27.07	25.71	33.38	31.24	29.00	27.02
	<0.125-0.063	Fine	11.87	9.51	8.31	7.88	8.20	6.90	7.00	4.95	9.34	8.26	6.61	7.38
	<0.063-0.032		1.59	1.05	0.74	0.61	0.70	0.57	0.64	0.29	0.54	0.53	0.33	0.54
	<0.032		0.11	0.14	0.18	0.14	0.10	0.16	0.13	0.16	0.16	0.18	0.20	0.14

Figure 3. Average percentual amounts w% for particleboard samples

Results from sieve analysis showed a difference between the amount of chips in the size ranges presented in the volume for MDFs and particleboards. Distribution of chips from particleboards showed the highest share of chips in the size range <0.500-0.250 mm, no matter of adjusted conditions, where the percentual weight share ranges from 34.7-40.8 %. In MDF, no matter of adjusted conditions, the highest share of chips was found in size ranges <0.250-0.125 mm which ranged from 38.1-50.7%. A noticeable amount of chips in sizes <0.032 mm were found in PTCB by ranges 0.1-0.2 % and in MDF by 0.1-0.6% where with a combination of (vf) 8m/min and (n) 20,000 revs/min reached 4.7 %. As was mentioned earlier sieve analysis can be misleading and thus, we will compare the amounts based on size ranges, which were divided into fraction sizes (coarse, medium, fine) according to [55] but Fine range was slightly modified and showing only sizes below <0.125 mm, for a closer approximation of dust size range.

Cutting conditions	Workpiece		MDF	MDF	MDF	MDF	MDF	MDF	MDF	MDF	MDF	MDF	MDF	MDF
	Width of cut (ae) [mm]		1	1	1	1	1	1	1	1	1	1	1	1
	Feed rate (vf) [m/min]		6	8	10	12	6	8	10	12	6	8	10	12
	Revolutions (n) [revs/min]		16,000	16,000	16,000	16,000	18,000	18,000	18,000	18,000	20,000	20,000	20,000	20,000
Size ranges [mm]	>2.00-2.00	Coarse	0.23	0.22	0.18	0.21	0.19	0.21	0.13	0.16	0.13	0.28	0.07	0.05
	<2.00-1.00		0.30	0.10	0.25	0.27	0.30	0.32	0.26	0.23	0.37	0.20	0.14	0.04
	<1.00-0.500	Medium	0.33	0.49	0.73	1.00	0.56	0.43	0.93	1.29	0.40	0.81	0.71	0.90
	<0.500-0.250		9.74	14.06	21.29	25.51	12.59	20.58	31.10	35.18	9.92	13.57	22.70	29.08
	<0.250-0.125		50.65	50.62	50.71	44.72	54.70	45.15	40.33	38.11	50.35	48.42	43.91	41.07
	<0.125-0.063	Fine	26.59	23.50	19.16	18.92	22.62	21.55	17.89	16.01	25.71	22.43	20.76	18.44
	<0.063-0.032		11.74	10.57	7.23	9.14	8.65	11.47	9.03	8.72	13.05	9.57	11.14	10.16
	<0.032		0.41	0.44	0.45	0.24	0.39	0.30	0.33	0.30	0.08	4.72	0.56	0.26

Figure 4. Average percentual amounts w% for medium-density fibreboard samples

From the point of size ranges (Figure 5-6), the number of chips in dust size <0.125mm (Fine) showed significant differences between PTCB and MDF ($p<0.05$). In PTCB samples milled at (n) 16,000revs/min increasing (vf) from 6m/min to 12m/min showed a steady lowering trend on percentual amounts from 1.6% to 8.6%. Trend followed even with adjusted (n) at 18,000 revs/min where the amount of fine chips lowered from 9% to 5.4%. With (n) 20,000 revs/min steady lowering trend was observed between (vf) 6m/min to 10m/min from 10% to 7.1%, but with (vf) 12m/min amount of fine chips grew to 8.1%. In MDF samples milled with (n) 16,000revs/min such a lowering trend was present also here, where increasing (vf) from 6m/min to 10m/min caused a drop from 38.7% to 26.8%, but again in (vf) 12m/min slightly higher amounts were observed by 28.3%. With (n) 18,000 revs/min from (vf) 8m/min to 12m/min was presented a straight lowering trend from 33.3% to 25% and with (n) 20,000 revs/min increasing value of (vf) from 6m/min to 12 m/min showed decreasing trend from 38.8% to 28.9%. In MDF, increasing the feed rate from 6-12 m/min or 8-12 m/min was proven on post-hoc tests as significant difference ($p<0.05$). Revolutions of the cutting tool 18,000 revs/min also showed the lowest percentual amounts of fine chips <0.125 mm compared to 16,000 revs/min and 20,000 revs/min no matter of machined workpiece, but statistically this difference was not proven as significant.

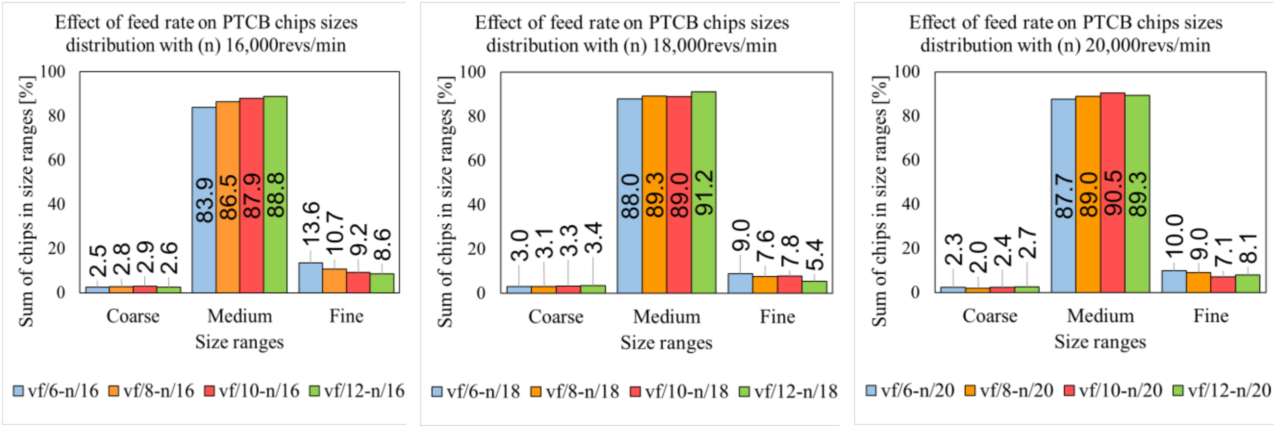

Figure 5. Average amounts of particle size distribution, with respect to feed rate and revolutions of the cutting tool, sorted by size ranges for particleboards (PTCB)

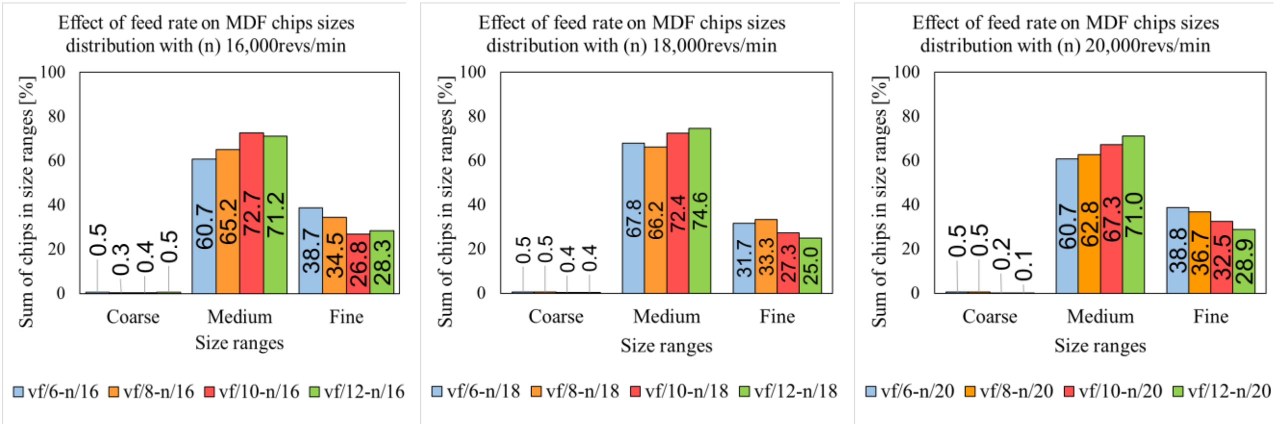

Figure 6. Average amounts of particle size distribution, with respect to feed rate and revolutions of the cutting tool, sorted by size ranges for medium-density fibreboards (MDF)

Analysing the effect of technological variables from the point of chips in sizes <10.0 μm (Figure 7) showed again that the lowest amounts were obtained with the revolutions of the cutting tool (n) at 18,000 revs/min. For easier interpretation of results values of revolutions are shortened to 16 (16,000 revs/min), 18 (18,000 revs/min), and 20 (20,000revs/min).

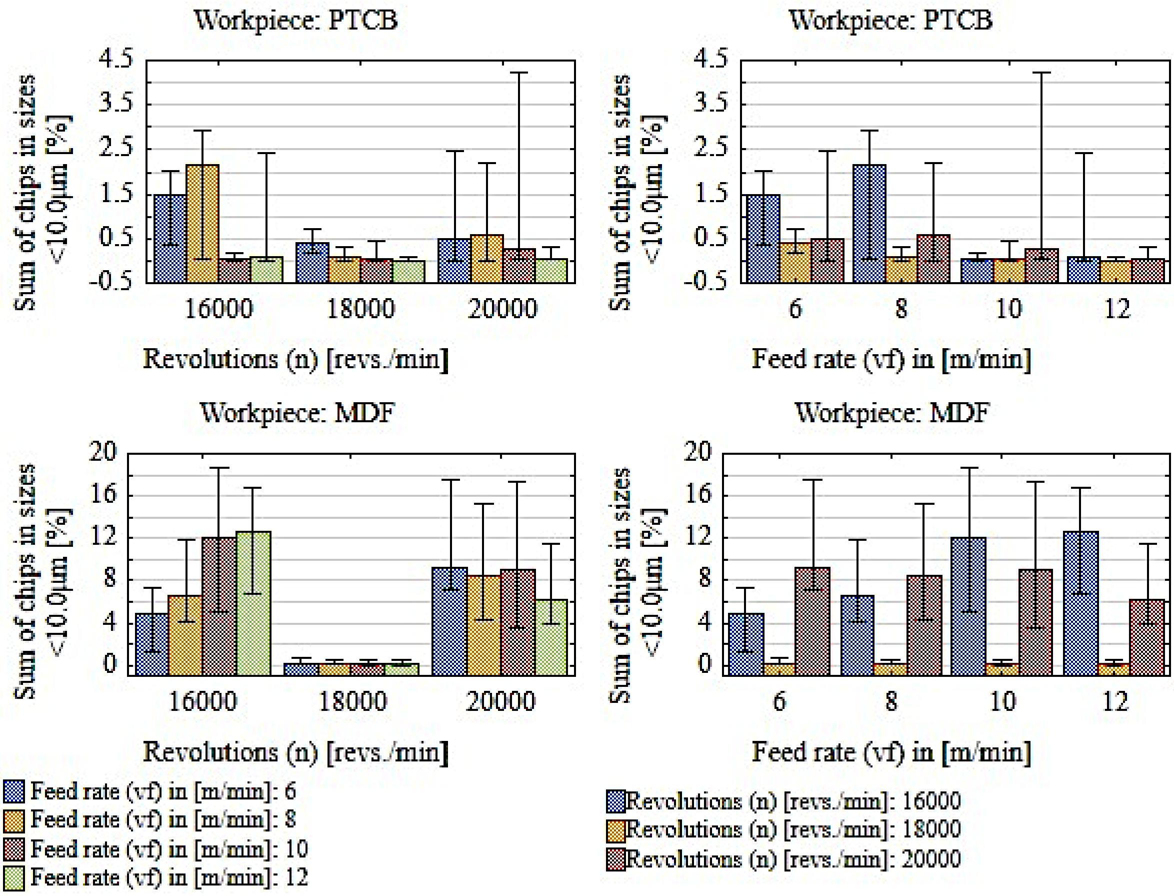

Figure 7. Effect of feed rate (vf) and revolutions of the cutting tool (n) on the sum of chips in <10.0μm sizes

Changing revolutions from 16,000 revs/min to 20,000 revs/min with adjusted (vf) at 6m/min showed in PTCB samples decrease from median value 0.13% between 16-18 to 0.04% and again grow to 0.14% between 18-20. In MFD samples between 16-18 were observed a decrease from 6% to 0.3% and again grow between 18-20 to 9%. Increasing value of (vf) to 8m/min showed in PTCB samples again decreased from 0.63% to 0.2% between 16-18 and increased up to 0.3% between 18-20. In MDF decreased from 6% to 0.1% between 16-18 and again increased to 7.7% between 18-20. Further increasing feed rate to (vf) 10m/min showed in PTCB increasing revolutions lead to an increase in amounts from 0.1 to 0.23% between 16-20. In MDF samples trend remained the same as in previous combinations, again amounts decreased from 8% to 0.2% between 16-18 and increased to 5.4% between 18-20. Lastly, with adjusted (vf) at 12 m/min in PTCB samples trend showed a decrease from 0.12% to 0.04% between 16-18 and an increase to 0.14% between 18-20. Samples of MDF follow a previous trend where between 16-18 was observed to decrease from 6.7% to 0.1% and later increase to 5.5% between 18-20. Due to the non-normal distribution of presented data, statistical calculations of post-hoc tests (Kruskal-Wallis) based on medians showed in MDF there is a significant difference ($p<0.05$) between 18000 revs/min compared to 16000 and 20000 revs/min no matter of adjusted feed rate (vf). In PTCB samples significant difference was found only in combinations of feed rate (vf) 6m/min and 8m/min between 16,000-18,000 revs/min ($p<0.05$), and with (vf) 10 and 12m/min between 18,000-20,000 revs/min ($p<0.05$).

Results showed that depending on conditions estimated amounts of chips in fine and in a potentially respirable <10.0μm sizes were different. For a better description of the findings with specific cutting conditions, we transformed those main variables to kinematic variable average chip thickness and verified if the proven kinematic variable would show similar behavior on distribution from the point of collected chips, representing amounts of chips created in the zone of chip creation, same as from the point of dust concentration of airborne particles [3],[19]. If the source of dust emission is in the cutting zone, applying the same approach may lead to a decrease in the presence of dust chips in collected form. We believe that this statement should be true in general and applying it to chip particles in the collected form from sieve analysis may cause a decrease. For estimating the value of average chip thickness in peripheral milling, we calculated its value in this CNC process from given variables with the formula described by [32].

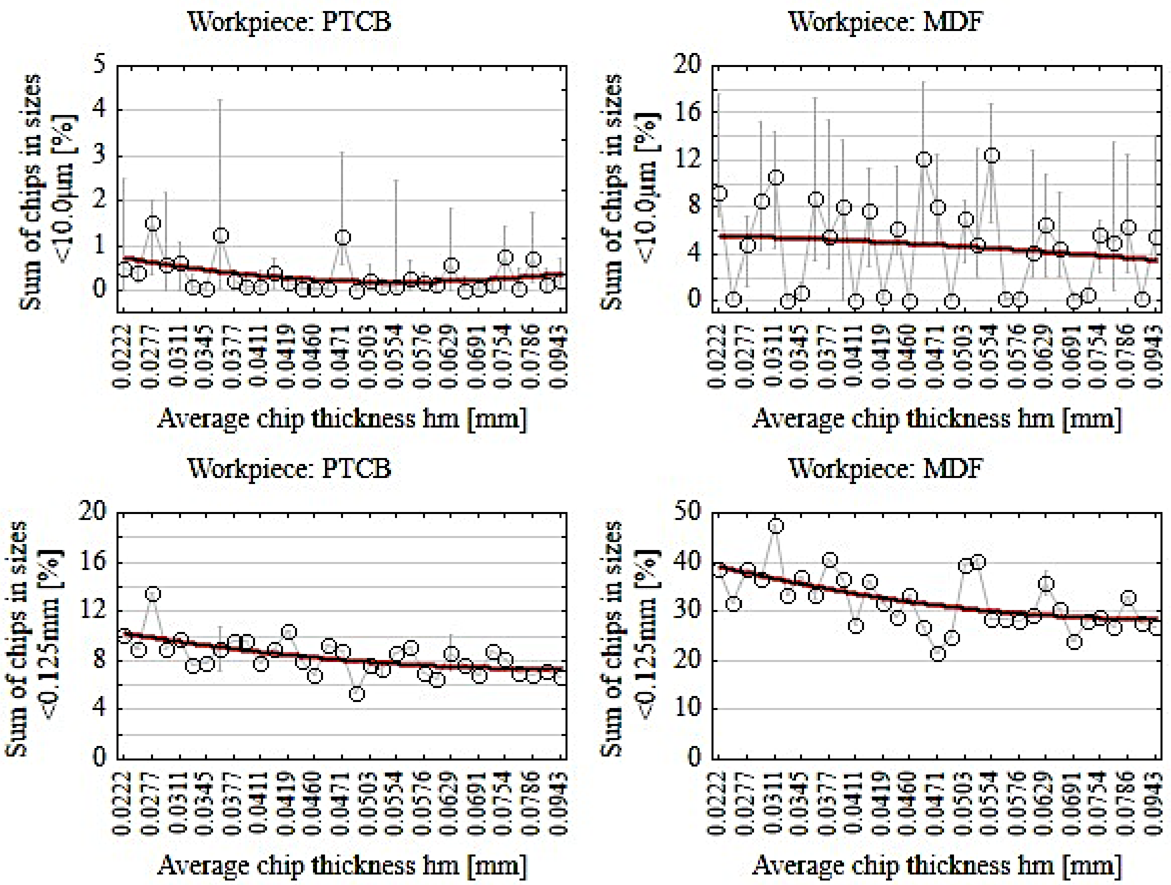

Figure 8 Effect of average chip thickness (hm) on the chips in the dust size <125.0μm and respirable size <10.0μm

As results showed there is no clear trend over the presence of chips in respirable and dust size with increasing the value of average chip thickness (hm). Percentual amounts of chips of sizes below <125 μm showed a decreasing trend as the value of average chip thickness increased in both materials. The percentual amounts of chips in respirable sizes <10.0 μm showed different trends depending on the workpiece. In the MDF samples trend line showed a decrease, but in PTCB samples only to value of (hm) 0.055 mm, and after this point percentual share started to grow again. Trend predictions were made by polynomic lines, however, the accuracy of such lines showed very low prediction accuracy (for <125 μm PTCB R2=0.85 and MDF R2=0.65, for <10.0 μm R2=0.2), and thus, the kinematic variable of milling average chip thickness showed no effect over chips in dust size and respirable sizes in collected from.

Analysis showed that tested wood-based materials produced different amounts of chips in dust and respirable sizes. In MDF compared to PTCB significantly higher content of fine chips <125 μm and respirable chips (25-39%; 18%) were found than in milling PTCB (5.4-10.0%; 4.5%). Its amounts varied as technological conditions have changed. As was hypothesized, the creation of wood dust must be associated with the chip creation and chip size and shape depend on technological conditions. Thus, technological conditions also must affect the wood dust. This hypothesis showed to be true because as technological variables feed rate, and revolutions of the cutting tools have changed even the presence of chips in those sizes changed. However, the relation between collected chip mass and airborne chips is to our best knowledge not studied, and comparing collected chip mass distribution obtained in such designed setups to dustiness coefficients or dustiness concentration is quite complicated.

For comparison with our results, in the article [15] authors studied the difference between profile milling of MDF on two devices with different revolutions of the cutting tool. Here authors obtained with the tool of diameter 140mm and adjusted revolutions 8000 revs·min^{-1} a chip in dust size range <125 μm approximately by 79.59% of chips in the total volume. For a combination of tool diameter 120 mm (4 cutters) and adjusted revolutions 12,000 revs·min^{-1} a volume by 63.06% of the total mass volume. Details are not listed, but some patterns may be present, and when changing revolutions from 8,000 to 12,000 revs·min^{-1} amounts of fine chips lowered same as in our case between 16,000 to 18,000 revs·min^{-1}. In the work [40], the authors studied distribution from drilling various wood-based materials. In drilling MDF (based on provided information – number of tooths 1; feed per revolution 0.1515 mm·rev^{-1}; revolutions 6,000 revs·min^{-1}, makes feed rate 0.9 mm·min^{-1} and chip thickness 0.038mm), chips of sizes <0.125 mm represented a mass volume 6.53% in MDF and particleboards by 14.69%, both from 1000g samples. The authors also studied the respirable sizes, in which PTCB and MDF create approximately similar amounts by 0.07% of chips in sizes <10.0 μm, but the closest point of our average chip thickness (0.0377 mm) we obtained in PTCB 0.2% and in MDF 6% of chips in respirable sizes. Interesting results were found in the article [59] where authors sawed on circular saw particleboards with tree various feed rates (12, 18, 24 m/min) and constant revolutions (4,720 rpm). Here authors showed that the number of chips in the size range <125 μm increased as the feed rate increased as well. Comparing those results of fine chips to our findings is in opposite. As was noted in the article [44] sawing feed rate could show a different behavior on particle distribution in this size range where authors milled different material laminate particleboard but also observed as the value of kinematic variable feed rate increased (velocity of the cut was optimized to vc=84.3 m·s^{-1} thus n=76.67 revs·min^{-1}) the content of chips in sizes <125 μm and even chips in size <10.0 μm has lowered. They explained it as the smaller feed rate denotes smaller feed per tooth and therefore smaller theoretical chip thickness (assuming the other dimensions are constant) producing lower dust and respirable chips. Here, we studied the average chip thickness which doesn't show a clear trend and thus, this statement may be true only for sawing.

In milling with a helix type of cutting tool, increasing the feed rate lowered the presence of fine chips and chips in respirable sizes only with specific conditions for PTCB (measured by medians) and MDF (only with n=20,000), and thus depending on machined materials technological conditions may lead to reducing the presence of dust and respirable chips differently. But it needs to be noted, that depending on the stage of tool wear such behavior will probably be also different. If materials are cut by a "sharp" (perfect geometry of the cutting wedge) wood or wood-based materials are cut and not deformed under the pressure of the blunted tip tool which probably deforms materials even by friction (based on promising results from article [60], where authors sawed on a circular saw a natural wood with a coated tool and reduce the presence of wood dust and probably coating on tool prolonged tool lifetime and wear doesn't occur or coefficient of friction was minimized), which could influence the creation of chips in those sizes. However, revolutions 18,000 revs•min-1 also showed in both materials significantly lowest amounts of chips in respirable sizes, and thus, feed rate may show affiliation to revolutions (kinematic variable, however, showed no clear relation) also differently based on the machined workpiece. However, we don't understand right now the mechanism that causes the creation of fine and respirable sizes, but we believe the specific revolution of the cutting tool is also associated probably with a different cutting mechanism.

4. Conclusion

In this experiment, we studied the effects of main operational parameters on the amounts of chips in dust-size ranges and the amounts of chips in potentially respirable sizes. Here, we varied the main milling conditions to obtain the lowest presence of the dust size and respirable chips in the collected mass volume. The dust size range was represented by the sum of chips in <125 μm and respirable sizes by size <10.0 μm. Here, we also transformed the main operational variables into the kinematic value of average chip thickness to verify if this variable shows a decreasing trend with increasing its value on studied sizes as was proven for airborne dust particles. The size ranges of the created chips were based on sieve analysis and actual sizes by laser analysis. The obtained findings of the experiment can be summarized like this:

- The percentual sum of chips in fine <125 μm size range and respirable sizes <10.0 μm created in milling was significantly ($p<0.05$) higher in MDF (25-39%; 18%) than in PTCB (5.4-10.0%; 4.5%).
- Increasing the variable feed rate from 6m/min to 12m/min significantly ($p<0.05$) lowered the percentual amounts of chips in fine <125 μm range and respirable sizes <10.0 μm in PTCB, no matter of adjusted revolutions. In the case of MDF only with revolutions at 20,000 revs·min^{-1}
- Significantly lowest amounts of chips in respirable sizes <10.0 μm were found with revolutions at 18,000 revs·min^{-1}, the mechanism that caused this effect is to us right now not known.
- Kinematic variable average chip thickness showed no clear decreasing trend as its value increased.

Results showed that the presence of dust and respirable chips may lowered by changing cutting conditions. We don't know yet the relation between the amounts of dust-like and respirable chips created in the cutting zone and the amount of airborne dust particles that pollute the surrounding air, but as was shown in available articles there is some predictable pattern with cutting data. Thus, we believe properly adjusted cutting conditions in the milling of wood-based materials especially MDFs may be used to achieve lower dust limits in manufacturing. For verifying and explaining the relation between collected and airborne presence of dust and respirable sizes further experiments are needed.

Acknowledgements
The project was supported by VEGA 1/0324/21 "Analysis of the risks of changes in the material composition and technological background on the quality of the working environment in small and medium-sized wood processing companies".

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