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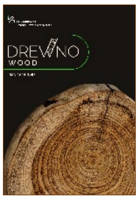

The Effect of Average Chip Thickness on The Potentially Respirable Dust from CNC Finish Milling of Wood-Based Materials

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Milling wood-based materials on CNC devices causes the creation of chips in small sizes that may escape the chip extraction zone to the surrounding environment and pollute the air. The article studied the effect of the feed rate (vf) and the width of cut (ae), transformed into kinematic average chip thickness, on the amounts of chips in respirable sizes <10.0μm created in the cutting zone from particleboards (PB) and medium-density fibreboards (MDF). The amounts of dust-sized chips are discussed and were determined by the sieving analysis. The sizes of potentially respirable chips were estimated by weighting with the laser diffraction method. The highest amounts of chips from PB were of 0.250-0.500 mm (38-41%w), but in MDF, amounts varied depending on cutting conditions. With (ae) 1 mm were in the size range of 0.125-0.250 mm (35-54%w), for (ae) 2 mm (33-35%w), and (ae) 3 mm (36-40%w) with combinations of (vf) 6-8 m·min-1. With a combination of (vf) 10 and 12 m·min-1 distribution moved to a higher size range. Chips in sizes 10.0-4.0 μm were estimated by <1%, for 4.0-2.5 μm <0.5%, in 2.5-0.1 μm <0.3%, and <0.1 μm by <0.05%. Statistically was proven (p<0.05) only in PB, with adjusted (ae) by 1 mm, increasing the value of (vf) from 6 to 12 m·min-1 and also with (vf) at 6 m·min-1, between values of (ae) 1 and 2 mm (hm of 0.025-0.035 mm), will significantly (p<0.05) lower the percentual amounts of chips in sizes 10.0-4.0 and 4.0-2.5 μm.

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Introduction

With the furniture market reaching a total global revenue of USD 694 billion in 2022, wood-based materials are a very important product (Statista, 2023). Materials such as particleboard (PB) and medium-density fibreboard (MDF) are essential raw materials for the furniture industry. Currently, their worldwide production is

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at more than 105 million m^3 - PB and over 127 million m^3 of fibreboard, including a significant share of MDF/HDF - around 111 million m^3 (FAO, 2023). In machining workpieces, to achieve the required shape and dimensions, according to the required level of accuracy and quality, the material must go through several technological operations. The usually used processes are mechanical cutting i.e. sawing, milling, surface grinding, and hole drilling. During mechanical cutting, the removed volume of material creates small layers of removed materials (called a chip, in AmE particle) which take on different shapes and sizes depending on used machining operation and cutting tool. The resulting swarf, depending on the dimensions it reaches, can have varying degrees of damage and potential for further use. The fine fractions with sizes below <100μm are called dust and, without any form of respiratory protection, it is possible to breathe them in, making them harmful to human health (Gómez-Yepes & Cremandes, 2011; Menze et al., 2021). The dust mixture is also composed of fine particles that can float in the air for long periods. Presence of the increased dustiness in the working environment remains a serious issue on multiple levels. For many years, wood dust has been recognised as carcinogenic to humans, according to the IARC (International Agency for Research on Cancer) (IARC, 2012). Moreover, the work (Mofidi et al., 2022) indicates that nasopharyngeal cancer (NPCs) and sinonasal cancer (SNCs) are two important cancers resulting from exposure to wood dust in workers exposed to airborne wood dust, with the most serious impact on workers' health being that of 0.1-10 μm (Rogoziński et al., 2021). These particles can enter the respiratory tract and settle in tissues of the respiratory system, also having an impact on the occurrence of asthma or chronic obstructive pulmonary disease (Holtjer et al., 2023). In addition, particles of this size in particular form can irritate the eyes and skin, leading to adverse health effects, including allergies and diseases (Alwis et. al., 1999, Barbosa et. al., 2018, Douwes et. al., 2017, Jacobsen et. al., 2021, Kminiak et al., 2021, Mračková et al., 2015). If the created chips are not extracted perfectly, those non-extracted very small chips (dust particles) will pollute the surrounding environment. The most effective way to minimize dust emission is directly reducing the dust generated in milling operation by optimizing cutting parameters (Pędzik et al., 2020). As stated, (i.e. Araujo et. al. 2009), particles between 1-100 μm originate from mechanical processes, thus, the source of dust emissions must originate from the cutting zone where a chip is created, between the cutting edge of the cutting tool and the machined material. From the technological point of view is possible to reduce dust presence. An example is the work of (Júda et al., 2023), where it was found that increasing the feed rate during finishing milling of MDF and particleboards on a modern 5-axis CNC milling center contributes to reducing the number of particles in the range of <0.125 mm and may be true even for smaller sizes. Material removal during milling depends on the required accuracy of final dimensions and final surface quality it is also dependent on 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, etc. Studying all variables 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. Recommended revolutions are usually pre-described by the manufacturers of cutting tools, based on machined workpieces, but sometimes are 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. Predicting the amount of dust particles created during milling which is based on the technological parameters is not a new idea. Studies published earlier (Pamqvist et. al., 1999, Hemillä et. al., 2003, Hursthouse et al., 2004, Kos et. al., 2004, Rautio et. al., 2007, Fujimoto et. al., 2011, Teng et al., 2014) found that different wood-based materials machined with different method will produce different amounts of dust in various sizes and morphological shapes. However, just a scarce amount of articles studied the modern CNC milling method, and operational variables were studied from the point of on very small dust sizes. Many authors in published papers (Pamqvist et. al., 1999, Hemillä et al., 2003, Rautio et. al. 2007, Piernik et al., 2019; Ratnasingam et al., 2009) show that the most significant factor affecting the amount of airborne dust created from milling is the average chip thickness. Those authors studied the effect of so- called average chip thickness on the presence of airborne dust particles from wood, MDF, and other wood-based materials. However, those results were proved only for airborne dust particles and not for the presence of dust created in the cutting zone. The general shape, thickness, and dimensions of chips vary because they depend on the machining type, parameters of the machining, the geometry of the cutting tool and its wear stage, the accuracy of aligning the CNC machining device and its stability, etc. In the peripheral cutting, the chip is moulded into a comma-shaped-like form, with the non-constant thickness of the cut. The average chip thickness is an informative variable, which provides a large amount of information on the cutting process itself (Gottlöber, 2023). It is possible to use it when comparing data from other types of milling processes as well. Thus, the factor of average chip thickness is applicable even for a collected mass of chips. Therefore, this article aims to determine the content of potentially respirable particles for size <10.0 µm in the whole mass created in differently adjusted milling parameters which were transformed into the kinematic variable average chip thickness.

Materials and methods

To cover the widest possible range of used wood-based materials in furniture industries for manufacturing parts, we bought for the experiment two different commercially available materials – particleboard (PB), for furniture and interior fitments (including furniture) for use in dry conditions (EN 312, 2010), and medium-density fibreboard (MDF) used for general- purpose use in dry conditions, particularly for interior fitments including furniture (EN 622-5, 2010). The main mechanical properties of machined workpieces are listed in Table 1. For easier manipulation and fixation on vacuum clamps of the CNC worktable, the delivered materials in the form of large dimensions were first cut on a K-500 circular saw (FELDER, Austria) into smaller blocks with dimensions of 500×300×18 mm. After the cut, the created sides were not sanded due to the possibility of contamination from sanding paper.

Here the experiment simulated the finishing stage of milling wood-based materials in the furniture industry. The milling experiment was carried out by using a 5-axis CNC machining center (SCM Tech Z5, Italy). As a cutting tool, here we used a standard helix-shaped end mill to eliminate the effect of the modernised non-solid shape of the helix. A new spiral shank milling cutter with a solid design of helix cutting edges with a shank diameter of 20 mm, tool diameter of 20 mm, tool length of 120 mm, cutting length of 60 mm, and number of flutes (z) 3, was used. During the experiment, the cutting tool was two times resharpened based on the manufacturer-provided data about the tool's lifetime, to eliminate as much as possible the effect of wear. During milling, we cut along the longest dimensions of the workpieces with a combination of adjusted technological parameters feed rate (vf), and widths of cut (ae). The revolutions remain constant at 18,000 revs·min^{-1} in the experiment.

Table 1. Basic properties of tested materials

Parameters	Units	Value of parameter
Dimensions (Length × Width × Thickness	mm	500 × 300 × 18
Density (ρ) of PB	kg·m^{-3}	≅ 680
Density (ρ) of MDF	kg·m^{-3}	≅ 720
MOE of PB	MPa	≅ 11
MOE of MDF	MPa	≅ 20
MOR of PB	MPa	≅ 1600
MOR of MDF	MPa	≅ 2200

Table 2. Machining conditions of the experimental setup

Parameters	Units	Value of parameter
Materials	-	Particleboard (PB), medium-density fibreboard (MDF)
Machining, direction	-	Milling, down-milling
Feed rates (vf)	m·min^{-1}	6; 8; 10 and 12
Widths of cut (ae)	mm	1; 2; 3
Revolutions of the cutting tool (n)	revs·min^{-1}	Constant, 18,000
Cutting tool	-	Solid carbide cutter (D20)

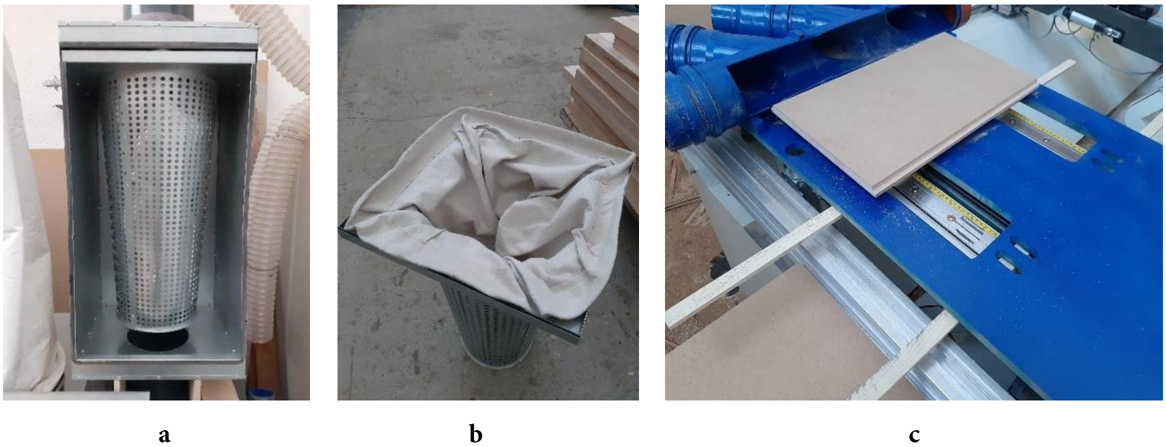

Fig. 1. Apparatus used in the experiment, where (a) – gathering box, (b) – filtration textile, and (c) – custom gathering hood

The rotation of the cutting tool, due to the direction of feed speed, was down milling (climb milling) commonly used direction in most furniture CNC milling processes. The conditions of the experiment are shown in Table 2.

To obtain representative samples for analysis which would contain all created chips in the milling, and due to limited options on how to collect them in the cutting zone, we needed to build a custom device. Our designed setup consisted of a gathering box (a), with a filtration textile (b) inside, and a custom hood (c) to which the chips will fall and be conducted on the filtration textile. Such a setup is shown in Fig. 1.

The extracting apparatus designed for this study was based on the pre-existing extraction device (STILER FM470) which served as a source of conducting air (FAN), and a custom- designed gathering box with an attached filtration textile (HEPA textile, type H13) which can collect at 99,8% of all particles below size < 0.2 μm. The created mass of chips from the milling process is sucked by the air stream from the extraction device and air conducts the chip mass samples to the attached filtration textile in the filtration box through PVC (antistatic PUR with surface resistance of R=10^3 ohm) hoses. Experimental samples were milled until approximately m = 50±1 g of the chip mass was collected, where this amount was purely based experimentally, Thus, different amounts of cuts were needed with differently adjusted widths of cut to obtain the required amounts. Detailed calculations showed, based on weighting collected and removed mass from workpieces on filtration textile, that our setup achieved in the case of PB's samples lowest efficiency (99,3%), and in MDF (98,2%). Thus, we believe our setup was sufficient for the presented experiment to estimate representative values for analysis. Determining potentially respirable chips in collected chip mass was done in two steps. In the first stage, the general particle size distribution of collected chip mass was determined with the use of standardized sieving analysis. A set of screens with mesh sizes of 2, 1, 0.500, 0.250, 0.125, 0.063, 0.032 mm, and a bottom collector (representing all sizes below <0.032 mm) were placed on a Retsch AS 200 vibrating screener (Retsch GmbH, Haan, Germany). Sieving parameters were with the recommendations (Kučerka et. al. 2008, Marková et al., 2016; Očkajová et al., 2018) for analysing wood dust, due to pre-made experiments where a high share of dust-size chips was found. The sieving was done with sieving interruption frequency each f - 10 s, amplitude – 2 mm, total screening time τ = 15 min. The proportions of the remaining mass of fractions on the sieves after the sieving process were determined on an electric laboratory balance scale Radwag 510/C/2 (Radwag Balances and Scales, Radom, Poland) with an accuracy of 0.001g. Based on the weighting of the retained masses, the particle size distribution was calculated. In the second stage, the potentially respirable sizes of particle content with the use of a particle size analyser (Analysette 22), working on the laser diffraction principle, within the retained chips of size range below <0.250 mm were determined. In this range, 5 measurements of the very fine mass concentration within specific size ranges (10.0– 4.0 μm, 4.0–2.5 μm, 2.5–0.1 μm, and <0.1 μm) using the dry method were conducted. For calculating the amounts, the particle size analysis software MaSControl (Fritsch, Idar- Oberstein, Germany) was used. In the experiment, two operational variables were transformed into average chip thickness based on Equation 1 (Gottlöber, 2023):

$$h_m = \frac{f_z \cdot a_e \cdot 360°}{\pi \cdot D \cdot \mathrm{arcos}\left(1 - \frac{2 \cdot a_e}{D}\right)} \cdot \sin\kappa \quad (1)$$

where:

h_m- average chip thickness [mm]

vf – feed rate, in [m·min^{-1}]

n – revolutions of the cutting tool [revs·min^{-1}]

D – the tool's diameter in [mm]

a_e – width of cut in [mm]

f_z – feed per tooth (chip load) in [mm], where the equation for its calculation is:

$$f_z = \frac{vf}{n \cdot z} \quad (2)$$

κ – cutting edge angle in [°], in the experiment equal to 90°.

Statistical analysis

For verifying the effect of technological variables on the fine dust content created in milling, the tested variables were subjected to statistical examinations with a significance level of 5% (95%) probability. Tests of normality in specific conditions, however, showed in most of the samples non-normal distribution, and thus, statistical calculations were only based on p-values from non-parametric one-way analysis of variances based on testing median values, where hypotheses were tested by post-hoc Kruskal-Wallis tests. The presented data were analysed by using the software Statistica v.13.1 (Tibco Software, Palo Alto, CA, USA). The results were calculated from 5 measurements for studied very fine chips with the average chip thickness (Table 5). Based on the formulated research problem and research objective, the main hypotheses were defined. The established hypotheses were tested at the level of significance α = 0.05 (95%).

The results of the sieve analysis

Particle size distribution of chips created in milling PB showed that most retained chips were within the size range 0.250-0.500 mm by approximately 37-40%w of the whole mass, no matter of adjusted cutting conditions, there was no change to higher or lower size limit presented. The second most distributed sizes of chips were in the size range 0.125-0.250 mm by approximately 25-31%. Studying lower sizes showed for the width of cuts by 1 and 3 mm, increasing feed rate increased the percentual volume of retained chips in the size range 0.125- 0.250 mm, 0.063-0.125 mm, 0.032-0.063 mm, but in <0.032 mm. For chips retained on the sieve of mesh size 0.50 mm, 1.00 mm, and 2.00 mm increasing the feed rate caused an increase in the retained amount of chips.

Changing the operational variables feed rate and width of cut showed no significant change in this distribution, but the changes in percentual distribution were present (see Tab. 3). For MDF (Tab. 4), the sizes of chips were mostly in size range 0.125-0.250 mm and in 0.250-0.500 mm. With adjusted (ae) 1 mm, most distributed sizes were chips in the size range 0.125-0.250 mm by approximately 38-54%. Width adjusted width of cut by 2 and 3 mm such size range remain most distributed with feed rates 6 and 8 m·min^{-1}, but as feed rate increased to 10 and 12 m·min^{-1} the most distributed were found in size range 0.250-0.500 mm, wherein (ae) 2 mm ranged by 36-41%w and for (ae) 3 mm by 38-40%w. Compared to PB chips, lower sizes of MDF chips do not show a clear downward behavior with an increasing feed rate. From sieve analysis, it is present that increasing the feed rate caused an increase in the particle size of chips and lowered the amount of very small chips. This effect is present clearly in PB. In MDF increasing feed rate shows its effect on chips in the size range 0.250-0.500 mm where the percentual amount significantly increased, and for chips in the size range 0.063-0.125 mm which leads to a decrease in the amount.

Table 3. Particleboard chips size distribution

Sieve mesh [mm]	ae1-vf6	ae1-vf8	ae1-vf10	ae1-vf12	ae2-vf6	ae2-vf8	ae2-vf10	ae2-vf12	ae3-vf6	ae3-vf8	ae3-vf10	ae3-vf12
2.0	0.03	0.01	0.09	0.08	0.04	0.04	0.08	0.08	0.05	0.09	0.13	0.06
1.0	2.95	3.10	3.17	3.34	3.12	3.13	3.03	3.47	2.98	3.39	3.72	4.00
0.5	18.36	21.22	21.99	24.65	20.40	22.23	23.53	24.84	19.32	22.78	21.99	25.01
0.250	**38.45**	**39.87**	**39.91**	**40.81**	**39.65**	**40.53**	**40.38**	**39.52**	**37.87**	**37.94**	**38.44**	**39.14**
0.125	31.20	28.17	27.07	25.71	28.96	27.23	26.02	25.25	29.37	26.60	26.90	24.61
0.063	8.20	6.90	7.00	4.95	7.14	6.25	6.37	6.31	9.29	8.40	7.97	6.58
0.032	0.70	0.57	0.64	0.29	0.55	0.46	0.48	0.40	0.99	0.69	0.73	0.49
Pan	0.10	0.16	0.13	0.16	0.14	0.13	0.11	0.13	0.14	0.11	0.10	0.10

Table 4. Medium-density fibreboard chips size distribution

Sieve mesh [mm]	ae1-vf6	ae1-vf8	ae1-vf10	ae1-vf12	ae2-vf6	ae2-vf8	ae2-vf10	ae2-vf12	ae3-vf6	ae3-vf8	ae3-vf10	ae3-vf12
2.0	0.19	0.21	0.13	0.16	0.10	0.13	0.08	0.07	0.06	0.10	0.06	0.10
1.0	0.30	0.32	0.26	0.23	0.17	0.23	0.13	0.18	0.15	0.07	0.11	0.26
0.5	0.56	0.43	0.93	1.29	0.36	0.35	1.19	1.84	0.66	1.22	2.40	3.19
0.250	12.59	20.58	31.10	35.18	19.06	27.34	**35.39**	**41.08**	27.54	34.39	**37.64**	**39.62**
0.125	**54.70**	**45.15**	**40.33**	**38.11**	**43.13**	**38.43**	35.05	32.97	**39.91**	**35.65**	31.59	29.21
0.063	22.62	21.55	17.89	16.01	23.65	19.86	18.46	14.57	19.60	18.54	17.31	16.05
0.032	8.65	11.47	9.03	8.72	13.10	13.33	9.51	9.03	11.67	9.82	10.48	10.91
Pan	0.39	0.30	0.33	0.30	0.44	0.32	0.18	0.27	0.40	0.22	0.40	0.64

Results from a study of the effect of average chip thickness on the finest dust

Based on the chip size distribution, there was a change in distribution with differently adjusted cutting conditions, which could show a similar change in fine sizes. The amounts of potentially respirable particles obtained with specific machining conditions varied as well in a wide range. Based on the obtained results, however, there is no clear effect between the potentially respirable dust with the operational variables.

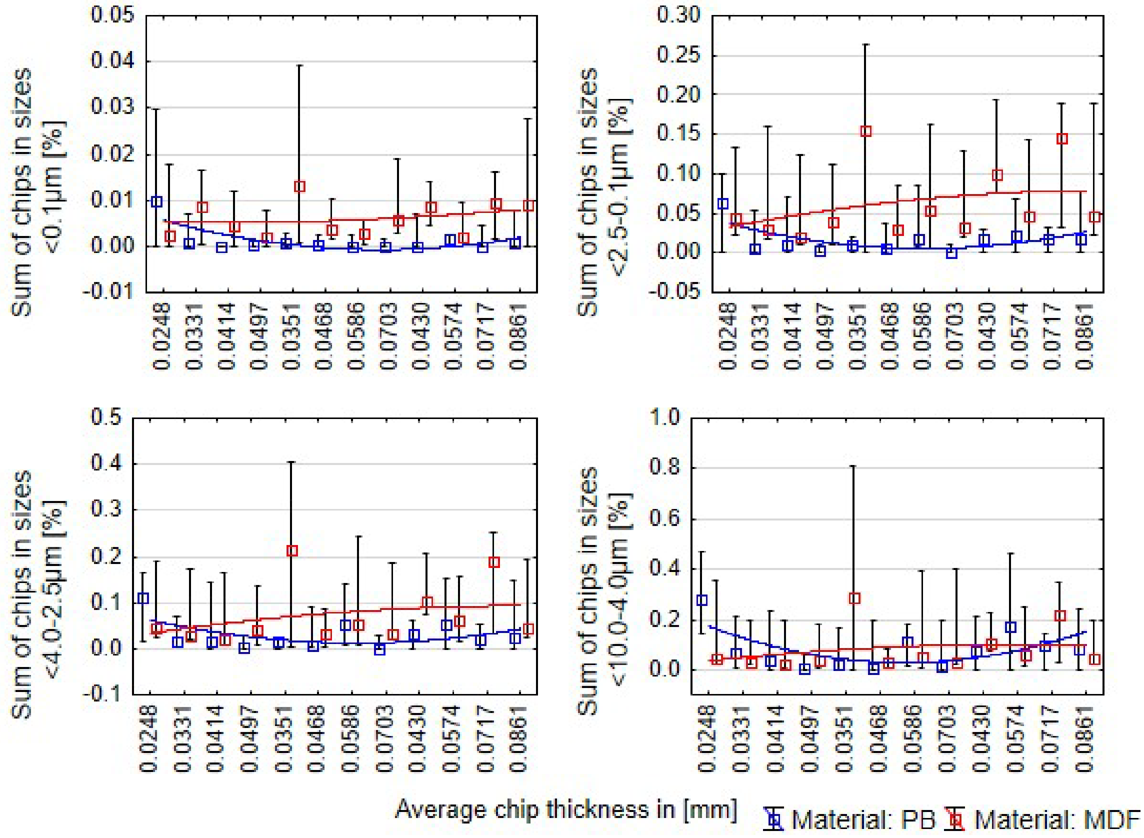

Fig. 2. The effect of average chip thickness on the percentual distribution of potentially respirable dust in various sizes

Calculating the average chip thickness and submitting the results to the specific value of the average chip thickness also showed no predictable behavior. To support this statement, for verifying the effect of average chip thickness on the potentially respirable amount of dust, results were subjected to trend lines for the average amount of specific size ranges and later for specific sizes. Fig. 2 plotted the average amount of dust present in specific size ranges, in which dust is distributed. The estimated values of the finest dust sizes in the whole mass of chips from both materials are significantly different and with specific conditions were obtained in different amounts. In both materials, the percentual amounts of chips in sizes 10.0-4.0µm do not exceed <1% of the whole collected mass, and smaller sizes showed even lower amounts. In MDF samples, the content of very fine chips in sizes between 10.0-4.0 µm, 4.0-2.5 µm, 2.5-0.1 µm, and 0.1-0.0 µm was found higher than in PB samples. The highest content in PB of chips in respirable size was obtained with a very small average chip thickness (hm) of 0.025 mm. The increasing value of (hm) caused a decrease in dust content between the thickness range of 0.025-0.05 mm. From this approximate point, the content of potentially respirable dust started to grow again. In MDF, a small value of (hm) 0.025 mm was observed with the lowest presence of those chips, and as the (hm) value increased, also the presence of those chips in respirable sizes. The dust content in studied sizes was for MDF based on median values higher compared to PB. However, fittings made by trending lines show some predictable patterns, but the predicting accuracy (R^2) was found very low, and thus obtained distributions cannot be proved. With laser analysis, it has been found that the presence of potentially respirable dust varies very differently based on technological conditions. In PB, the content of dust in the size range 10.0-4.0 µm is 0.47%, and for MDF around 0.81% in collected samples. Smaller size ranges in PB range from 0.03 to 0.17%, and for MDF approximately from 0.04 to 0.41%, from the point of collected chip mass, the effect on the particle size distribution with the average chip thickness is not clear, because the dust contents in particular size ranges seem randomly to jump up and down.

Results of statistical tests of variances

As was shown, some pattern was observed with increasing value of average chip thickness on percentual amounts of very fine chips, but predicting trend lines showed small accuracy and thus such distribution must be affected differently or by the main technological variables. For testing such a hypothesis, we tested H1: *We assume that the influence of main technological parameters such as feed rate and width of cut will be demonstrated by the relationship on the percentual distribution in the mass. A statistically significant difference was calculated between the measured data.* Analysing the results of statistical calculations showed only in PB samples, that with adjusted (ae) by 1mm increasing value of (vf) from 6m·min^{-1} to 12m·min^{-1} was significantly different ($p<0.05$) for chips in sizes 10.0-4.0 µm and 4.0-2.5 µm, but in other combinations, no significant differences were found. This represents values of hm by 0.025 mm and 0.049 mm, which showed in both plots a decrease with increasing its value. Thus, compared to the results published earlier there may be a relation between collected chips in respirable sizes and airborne dust particles. Verifying the effect of (ae) also showed that there is only a significant difference ($p<0.05$) in PB samples, milled with adjusted (vf) 6m·min^{-1} between values of (ae) 1 and 2 mm. In MDF samples combinations showed rarely a difference below ($p=0.9$).

Discussion

The presented article tried to clarify two facts: first - the source of dust emission in working factories is in the cutting zone, where the chip is created, and second, based on the theories where particles between sizes 1-100µm originated from the mechanical process, technological conditions are associated with the creation of chips in dust and respirable sizes and their changing (represented as average chip thickness) may lead to reducing the presence in the cutting zone. We tested these statements on two different wood-based materials. Due to our best efforts, we cannot say we prove or reject any of this statement. Sieve analysis and the presence of chips in respirable sizes varied significantly between tested materials and each material will produce different amounts of those chips. Changing cutting conditions was statistically proven only in PB samples, where milling with adjusted width of cut at 1 mm increasing feed rate from 6 to 12 m·min^{-1} will significantly reduce the percentual amounts of chips in sizes 10-4 µm and 4-2.5 µm and also the same effect with adjusted feed rate at 6 m·min^{1} changing the value of width of cut from 1 to 2 mm. A similar observation in sawing on the circular saws the solid wood (*Pinus sylvestris L.*) was observed in the article (Piernik M., et. al. 2019) where the authors also demonstrated that the larger the width of the cut (2.0 mm compared to 0.5 mm), the smaller the proportion of chips in the monitored sizes (10.0-4.0 µm a <4.0 µm) was observed. This statement also contributes well to results from (Nasir V. and Cool J. 2019-2020) where sawing solid wood materials

(*Pseudotsuga Menziesi L.*) where authors also demonstrated that the width of the cut has the most significant effect from the point of view of sawing growing trees on the removal of the airborne wood dust and it also showed a significant change in laminated boards to the proportion of the fine fraction of chips in sizes <10.0 μm.

Comparing the effect of feed rate in articles (Nasir V., and Cool J. 2020) authors also find that changing the value of the feed rate also leads to dustiness reduction. Based on these research and measurement results, it is quite possible to state that the dependence between the technological conditions, which they demonstrated from the point of view of financial representation, but also from the point of view of the mass part, exists and is not just about random phenomena present during the experiment.

From the results of the average chip thickness authors (Palmqvist & Gustafsson, 1999) stated that the average chip thickness should be above >0.1 mm, but (Gottlöber, 2023) recommends this value only >0.05 mm. In a presented experiment, this is quite in opposite, especially for particleboards because in those values amounts of studied chips in respirable sizes were growing up and not lowered. In the MDF samples, the value of hm above > 0.05 mm showed adecreasing effect, but without proven statistical significance. The problem with the average chip thickness it requires, to meet the criteria, increasing the feed rate or lowering revolutions of the cutting tool, which would also lead to an increase in feed per tooth (chip load) to the point that is questionable if the commercially available cutting tools can handle such feeds per tooths without significantly lowering its lifetime and ability to cut. The high feed per tooth increases tool wear, worsens the surface quality, and leads to premature tool failure (Ashworth et al., 2022; Kwidziński et al., 2021; Siklienka et al., 2016; Vitchev, 2019; Wachowicz et al., 2023). It is important to note in the end, our results could be heavily influenced by the wear stage of the cutting tools or low chip load, which was present when increasing the feed rate from 6 to 12 m·min^{-1} and thus further research is needed with higher feed rates, including even the newer modernised cutting tools of higher diameters.

Conclusions

In this experiment, we studied the effects of main operational parameters on the amounts of chips in potentially respirable sizes. Here, we varied the main milling conditions and transformed them to the kinematic variable of average chip thickness to obtain the lowest presence of the dust size and respirable chips in the collected mass volume and prove that technological variables may be used to lower the presence of dust and respirable chips. Our findings may be summarised:

- Estimated amounts of chips in respirable sizes haven't exceeded 1% of the volume.
- Changing the feed rate from 6 to 12 m·min^{-1} only in milling particleboards with adjusted width of cut by 1 mm will significantly lower the presence of chips in sizes 10.0-4.0 μm and 4.0-2.5 μm, in MDF no such effect was observed. By the means of values of the average chip thickness, changing the value of (hm) from 0.025 mm to 0.05 mm.
- Similarly milling particleboards with an adjusted feed rate of 6 m·min^{-1} and changing the width of cut from 1 to 2 mm will significantly lower the presence of chips in sizes 10.0-4.0μm and 4.0-2.5μm, again in MDF no such effect was observed. By the means of the value of average chip thickness, changing the value of (hm) from 0.025 mm to 0.035 mm.

Average chip thickness showed based on trend lines an unclear relation to the percentual presence of studied respirable size of chips. In PB samples increasing its value lowered the presence of those chips, but in MDF such increasing caused an increase. The accuracy of such prediction was in both materials very low, and we cannot say from the point of chip creation whether it's true or not, but some effect was observed and may be heavily affected by the stage of wear, even to our best effort of its minimalization in the experiment.

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