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Granulometric Characterization of Wood Dust Emission from CNC Machining of Natural Wood and Medium Density Fiberboard

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Abstract: The aim of this paper was to determine the particle size composition of wood dust emission from CNC milling of natural wood and medium-density fiberboard (MDF) and evaluate the associated occupational exposure risks. The paper is focused on some of the most commonly used materials in the woodworking and furniture industry, i.e., solid wood (beech, oak, and spruce) and composite materials (MDF panels). In addition to the influence of the machined material, the effect of the technical-technological parameters, namely, feed speed and depth of cut on the particle size distribution, was also investigated. The selected values of the technical-technological parameters used in this study followed the common work practice in small wood processing companies. The particle size distribution was evaluated by using sieve analysis of samples from the total mass of collected wood dust. The results demonstrated that machining of natural wood is characterized mostly by the formation of coarse dust fractions (2 mm–1 mm sieves), whilst the processing of MDF was associated with generation of fine dust fractions with a size below 100 μm. The results obtained can be used for optimizing the technological programs of CNC milling machines, thus, reducing the occupational exposure to harmful wood dust emissions in the wood-processing industry.

Keywords: occupational health; wood-based composites; medium density fiberboard; wood dust; particle size distribution; CNC machining

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1. Introduction

The workability of natural wood and wood-based materials is almost always associated with the formation of different fractions of particles that disperse in the air and inside the production premises, posing serious occupational health risks for workers [1–5]. By-products from woodworking processes, such as sawdust and wood dust, can have adverse effects on human health if they are not sufficiently controlled and effectively aspirated by dust extraction systems [6–9]. Computerized numerical control (CNC) machines appear to be problematic devices from the point of view of dust extraction equipment and suction of the smallest wood particles, as the particle remains in the working space of the CNC machine. Wood and wood-based material processing plants with improved working conditions can increase the precision of production or the reliability of finished products, thus, strengthening their position on the market [10]. Large companies do not have a problem with the transition to modern CNC technology, but in the case of small ones, it is, in many cases, complicated. It creates many technical and technological problems for them, and increased dust in the workplace is one of them [11–15].

A significant proportion of the accumulated wood particles that are not displaced by suction represent a health hazard for workers [16]. The particles lose momentum after hitting the edge of the suction basket and fall on the workpiece, on the clamping beams, or into the so-called collecting trough under the workpiece. The usual practice of the operator is to clean (blow) the surface of the furniture blank, as well as the clamping beams, using compressed air after the completion of all technological operations [17]. The worker, thus, sends the accumulated particles airborne (especially the fine dust fractions) not only in the working space of the CNC machine but also in the space of the entire workshop. Thus, the operator is directly exposed to fine dust particles, and also, dust dispersed in the air may constitute a fire and explosion hazard, which poses an immediate health risk [18,19].

Occupational exposure to wood dust can cause significant non-reversible human health problems, including skin, eye, and nose irritation [20]; asthma [21]; skin disorders (dermatitis) [22]; and adverse respiratory system effects, including decreased lung capacity, chronic obstructive pulmonary disease, and allergic reactions [23,24], as well as toxic effects specific to some wood species. Markedly, wood dust has been classified as carcinogenic to humans (Group 1) by the International Agency for Research on Cancer (IARC) [25]. According to IARC, wood dust causes cancers of the nasal cavity, paranasal sinuses, and nasopharynx, which have been observed mostly among workers exposed to hardwood dust. The recent European Union (EU) directives also classified hardwood dust as carcinogenic to humans and set an occupational exposure limit (OEL) of 2 mg $\cdot m^{-3}$ of inhalable hardwood dust fraction calculated or measured for a reference 8-h period with a transitional limit value of 3 mg $\cdot m^{-3}$ until January 2023 [26]. In addition, in 2002, the Scientific Committee for Occupational Exposure Limits (SCOEL) of the EU stated that wood dust exposure higher than 0.5 mg $\cdot m^{-3}$ can cause pulmonary effects and, thus, should be avoided [27]. It is more likely for people whose occupations are associated with wood dust exposure to develop various diseases associated with respiratory problems, including lung cancer. The risk of lung cancer has increased in those who have been exposed to wood dust for more than 10 years and have taken more than 40 years of occupation since the first exposure [28]. In addition, wood dust is considered to be one of the ten most common causes of occupational asthma. Dust toxicity depends largely on the type of wood raw material and products based on lignocellulosic raw materials, which results from the different content of chemical components and the hardness of the raw material [29].

The extent of harmful effects of wood dust to humans depends on many factors, such as the characteristics and size of dust particles, their concentration in the air, the duration and conditions of their action, and the sensitivity of each individual to the dust particles. In general, these dust fraction characteristics depend on the processing technology and machinery used, machining parameters, and type of processed wood material. Several studies reported very similar particle size distributions between pine and oak; others reported that hardwood dust is finer than softwood dust [25]. Depending on the treatments to which wood has been subjected before machining, dust can contain preservatives, additives, or adhesives [30–38]. The greatest occupational risk is caused by the finest dust particles (inhalable fraction), which, when dispersed in the ambient air, can lead to serious short-term and long-term human health problems [39,40]. Therefore, in order to select and implement the necessary preventive measures, it is essential to know the characteristics of the machined natural wood and wood-based materials, as well as their properties [41–44].

Since problems associated with exposure to wood dust were confirmed by many epidemiologic studies, producers have made great efforts to minimize it. There are three basic ways to reduce the hazards arising from occupational exposure to wood dust, namely, the selection and application of proper technological parameters of processing to minimize the creation of the most dangerous dust fractions; use of dust control and dust extraction and filtration systems, and/or use of proper respiratory protective equipment, such as face masks [45–49].

The aim of this paper was to analyze the particle size composition of wood dust emission from CNC milling of natural wood and medium-density fiberboard (MDF) and evaluate the associated occupational exposure risks to the health and safety of employees in the wood-processing industry.

2. Materials and Methods

2.1. CNC Machine

The experiments were carried out on a 5-axis CNC machining center SCM Tech Z5 manufactured by the company SCM Group, Headquarters Via Emilia 77, 47,921 Rimini (RN), Italy. The basic technical parameters of the machining center given by the manufacturer are provided in Table 1.

Table 1. Technical and technological parameters of CNC Machining Centre SCM Tech Z5 used in this work.

Useful desktop	x = 3050 mm, y = 1300 mm, z = 300 mm
Speed X axis	$0 \div 70$ m·min^{-1}
Speed Y axis	$0 \div 40$ m·min^{-1}
Speed Z axis	$0 \div 15$ m·min^{-1}
Vector rate	$0 \div 83$ m·min^{-1}
Parameters of the Main Spindle Electric Spindle with HSK F63 Connection	
Rotation axis C	640°
Rotation axis B	320°
Revolutions	$600 \div 24{,}000$ rpm
Power	11 kW 24,000 rpm
	7.5 kW 10,000 rpm
Maximum tool diameter	D = 160 mm
	L = 180 mm

2.2. Tool Parameters

The characteristics of the tool used were as follows: a shank cutter with one reversible cutting insert with the designation KARNED 4451, manufactured by Karned Tools, s.r.o., Praha, Czech Republic (Figure 1), was used in this experiment. The basic technical and technological parameters given by the manufacturer are provided in Table 2. Reversible cutting inserts HW 49.5/9/1.5 made of the sintered carbide material T10MG were mounted in end mills from the company BOTO, s.r.o., Nové Zámky, Slovakia. The basic technical parameters of the sintered carbide material given by the manufacturer are provided in Table 3.

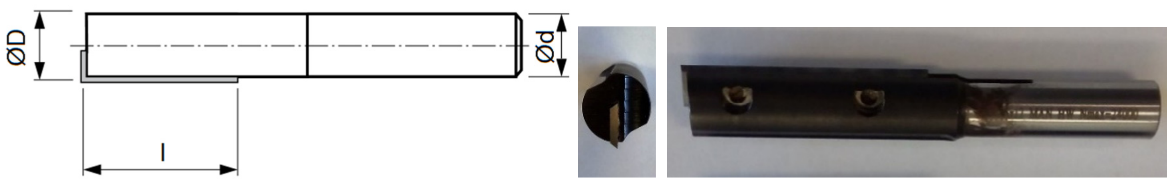

Figure 1. End mill used in the experiment-KARNED 4451 (ØD—working average, l—working length, Ød—clamping diameter).

Table 2. Technical and technological parameters of the milling cutter.

Miller	Working Diameter D [mm]	Working Length l [mm]	Diameter of the Chucking Shank d [mm]	Dimensions of Used Blades L × W × T [mm]	Blade Material
KARNED 4451	16	49.5	12	49.5 × 9 × 1.5	T10MG

Table 3. Technical parameters of sintered carbide tigra.

Classes of TIGRA	ISO CODE	US CODE	Binder %	Hardness		Bending Strength	
				HV10	HRA ± 0.2	N/mm^2	Psi
T10MG	K10-K40	C3+	10	1650	92.3	3600	522,000

A milling cutter tool with reversible cutting inserts was selected for conducting the experiments because it is a frequently used tool in small woodworking companies due to low operational costs (the tool does not need to be reground; in case of dullness, only reversible cutting inserts will be turned or replaced). In addition, this tool has zero inclination to the main cutting edge (the cutting edge is parallel to the tool axis), and thus, there is mainly axial removal of particles.

The production of furniture blanks was chosen for the purpose of the experiments. Roughly formatted blanks are finished to nominal size by milling on a CNC machining center (created either by sawing on a formatting circular saw or by nesting milling directly on the CNC machining center) with subsequent technological operations to create technological holes for connectors and fasteners. This represents the so-called finishing technological operation (milling in which the final part is created from the workpiece, where the machining allowances from the side edges of furniture blanks are removed.

This allowance can range from 1 mm (typical machining allowance) to 5 mm (limiting thickness of residual material in nesting milling), depending on the type of previous technological operation. An accompanying phenomenon of milling is that a considerable number of particles formed are not sucked out (production variability requires universal suction baskets typical of their large dimensions and axial outlet for suction pipes). The particle leaves the tool due to the centrifugal force in the radial direction and the individual particles have considerable kinetic energy and fall on the workpiece, on the clamping beams, or into the so-called collecting trough under the workpiece, and they remain in the working space of the CNC machine.

2.3. Workpiece

Tangential furniture blanks with moisture content w = 8% ± 1% from two commonly used hardwood species, i.e., common beech (*Fagus sylvatica* L.) and sessile oak (*Quercus petraea* (Matt.) Liebl.), and one softwood species, Norway spruce (*Picea abies* L.), were used to conduct the experiments. Wood samples were obtained from the School Forest Enterprise (ŠLP) Lieskovec of the Technical University in Zvolen and machined along the material.

The dimensions of the furniture blanks used were as follows: thickness h = 20 ± 0.25 mm, width š = 80 ± 0.25 mm and length l = 500 ± 1 mm. The blank surfaces were machined by face milling. Each sample blank was manipulated from a different pillar cutout within a given combination of the technical and technological parameters, i.e., feed speed/and depth of cut.

In addition to raw wood, MDF boards were used, popularly used in the production of furniture and interior finishing products. The production of this type of medium and high density wood material accounts for almost 30% of world production compared to all types of wood-based panels (based on FaoStat data from 2019). Raw MDF panels manufactured by the company Kronospan Polska sp. z o.o., ul. Waryńskiego 1, PL-78-400 Szczecinek, Poland, were used for conducting the experiments. The main technical characteristics of the MDF panels used in this work are presented in Table 4. The processed MDF blanks had a thickness h = 20 mm, width = 500 mm, and length l = 500 mm. The density of MDF panels was 750 kg.m^{-3}.

Table 4. Technical parameters of the raw MDF panels used in this work.

Property	Test Method	Request
Thickness tolerance	EN 324-1 [50]	±0.3 mm
Dimensions tolerance	EN 324-1	±5.0 mm
Squareness tolerance	EN 324-2 [51]	±2 mm.m^{-1}
Humidity	EN 322 [52]	4 ÷ 11%
Formaldehyde release	EN ISO 12460-5 [53]	<8 mg/100 g a. s. samples
Thickness range		6–9; 9–12; 12–19; 19–30; 30–45 (mm)
Bending strength (modulus of rupture)	EN 310 [54]	23; 22; 20; 18; 17 (MPa)
Tensile strength	EN 319 [55]	0.65; 0.60; 0.55; 0.55; 0.50 (MPa)
Thickness swelling (24h)	EN 317 [56]	17; 15; 12; 10; 8; (%)
Modulus of elasticity	EN 310	2800; 2500; 2200; 2150; 1900 (MPa)

2.4. Milling Parameters

The workpiece was milled with an end mill under the following conditions: depth of cut e = 1, 3, and 5 mm; cutter speed n = 20,000 min^{-1}; feed speed vf = 1, 3, and 5 m min^{-1}. For each combination of parameters, six samples were milled.

Samples for particle size analysis of wood dust were taken isokinetically from the exhaust pipe of the CNC woodworking center in accordance with the STN ISO 9096:2021-02 (83 4610) standard [57]. The particle size distribution was determined by sieving. A special set of stacked sieves was used for this purpose (2 mm, 1 mm, 0.5 mm, 0.25 mm, 0.125 mm, 0.063 mm, 0.032 mm, and bottom) placed on the vibrating stand of the screening machine Retsch AS 200c (Retsh GmbH, Haan, Germany). The sieving parameters were in accordance with ISO 3310-1 [58]: sieve interruption frequency 20 s, network deflection amplitude 2 mm.g^{-1}, screening time τ = 15 min, weight 50 g. The particle size distribution was obtained by weighing the proportions remaining on the sieves after sieving on an electric laboratory balance Radwag 510/C/2 (Radwag Balances and Scales, Radom, Poland) with weighing accuracy 0.001 g. Screening was performed on three samples for each combination of parameters.

Multi-factor statistical analysis of variance (ANOVA) was carried out to discern significant difference at 95% level of confidence, using specialized SAS software program (version 9.2, Cary, NC, USA).

3. Results and Discussion

It is possible to sort out the investigated materials into two groups from the point of view of the obtained results of the composition of the majority of the particles into particle grain size level. The first level consists of natural wood, in which we can characterize most of the particles as an area with a tendency to roll in the direction of particle separation. The second level consists of composite material MDF, of which the majority is formed by the dust particles, on the other hand.

In the case of natural wood, the majority share was formed by the so-called coarse fractions (fractions collected on the 2 mm and 1 mm sieve), followed by the medium-coarse fractions (collected on the sieves 500 µm and 250 µm), and the smallest percentage had the so-called fine fractions (collected on a 125 µm sieve, 63 µm, 32 µm, and bottom). In the case of MDF panels, the results were reversed, i.e., the coarse and medium-coarse fractions were almost negligible, and the largest amount of wood particles was found among the fine dust fractions, as seen in Table 5.

Table 5. Average particle size distribution according to individual combinations of monitored parameters: depth of cut, e, feed speed, vf.

Sieve Mesh [mm]	Fraction Type	Beech, Thickness 22 mm, Cutting Insert								
		I.	II.	III.	IV.	V.	VI.	VII.	VIII.	IX.
		vf1-e/1	vf3-e/1	vf5-e/1	vf1-e/3	vf3-e/3	vf5-e/3	vf1-e/5	vf3-e/5	vf5-e/5
2.000 1.000	coarse	94.2	96.86	95.36	90.58	75.5	66.85	67.22	47.24	46.94
0.500 0.250	medium coarse	3.09	2.03	3.68	5.95	19.09	29.49	21.27	36.69	47.38
0.125 0.063 0.032 <0.032	fine	2.68	1.12	0.95	3.46	5.41	3.67	11.51	16.07	5.67
Sieve mesh [mm]	Fraction type	Oak, thickness 22 mm, cutting insert								
		I.	II.	III.	IV.	V.	VI.	VII.	VIII.	IX.
		vf1-e/1	vf3-e/1	vf5-e/1	vf1-e/3	vf3-e/3	vf5-e/3	vf1-e/5	vf3-e/5	vf5-e/5
2.000 1.000	coarse	90.56	82.71	81.89	74.85	80.72	64.19	58.91	50.96	55.51
0.500 0.250	medium coarse	3.86	11.91	13.56	17.85	13.53	30.47	26.06	35.37	38.9
0.125 0.063 0.032 <0.032	fine	5.57	5.38	4.56	7.3	5.75	5.34	15.03	13.66	5.59
Sieve mesh [mm]	Fraction type	Spruce, thickness 22 mm, cutting insert								
		I.	II.	III.	IV.	V.	VI.	VII.	VIII.	IX.
		vf1-e/1	vf3-e/1	vf5-e/1	vf1-e/3	vf3-e/3	vf5-e/3	vf1-e/5	vf3-e/5	vf5-e/5
2.000 1.000	coarse	64.12	73.4	65.1	67.3	57.1	59.69	65.16	52.04	63.33
0.500 0.250	medium coarse	24.48	18.39	25.34	21.16	32.23	33.23	22.17	37.54	31.2
0.125 0.063 0.032 <0.032	fine	11.39	8.22	9.56	11.54	10.68	7.09	12.67	10.42	5.47
Sieve Mesh [mm]	Fraction type	MDF, thickness 22 mm, cutting insert								
		I.	II.	III.	IV.	V.	VI.	VII.	VIII.	IX.
		vf1-e/1	vf3-e/1	vf5-e/1	vf1-e/3	vf3-e/3	vf5-e/3	vf1-e/5	vf3-e/5	vf5-e/5
2.000 1.000	coarse	0.51	0.36	0.32	0.43	0.38	0.27	0.31	0.32	0.28
0.500 0.250	medium coarse	1.14	1.8	2.82	1.63	1.8	5.62	0.96	2.86	9.61
0.125 0.063 0.032 <0.032	fine	98.35	97.83	96.87	97.94	97.82	94.11	98.71	96.82	90.1

From the point of view of the weight share of coarse fractions, their total weight representation was comparable in the case of beech and oak, beech (46.94% ÷ 96.86%) and oak (50.96 ÷ 90.56%), whereas a large part was formed by particles over 2 mm. In the case of softwood material (spruce), the coarse fraction represented a smaller proportion (52.04% ÷ 73.4%), and the fraction ratio above 2 mm and below 2 mm was balanced. Graphical representation of the coarse dust fractions is presented in Figures 2 and 3. Coarse fractions consisted of particles called leaf (length and width exceeded the particle thickness several times). This corresponds to the intensity of differences in the structure of early and late wood, which grows in the range of spruce, oak, beech, as well as the individual physical and mechanical properties of wood when the values of spruce vary in other intentions (lower values) than beech and oak. From the point of view of the influence of technical and technological properties, it was not possible to observe a clear influence of the feed rate, although it could be expected that as the feed rate increases, the thickness profile changes (nominal particle thickness increases,) which affects the force ratios in the particle and its disintegration (development corresponds to the given theory within the particle size distribution of beech) [44]. With regard to depth of cut, it is possible to generalize the trend that as the depth of cut increases, the proportion of coarse fractions decreases due to particle elongation with unchanged nominal thickness. This trend was also confirmed by previous studies [59].

Data collected were subjected to multi-factor statistical analysis of variance ANOVA, performed separately for each particle grain size grade. It was determined that during the machining of MDF panels, no particles having the size of 500 μm and higher were formed, while in the case of natural wood, there were significantly more of them, as shown in Figures 2–4. We can also define the particles as 'leaf' within the given grain size grades. The initial zone of particle growth is the primary source of the given fractions (milling process is opposite, particle thickness increases from zero to maximum) in terms of particle crushing mechanism, and therefore, within beech and oak particles, it was possible to observe the influence of technical and technological factors. The particles friability increased with increasing the feed rate. Thus, the proportion of the given fractions increased, and it elongated the particle with increasing depth of cut, flattening the thickness profile. However, the statement does not correspond to the course of machining in the case of spruce where the development is ambiguous, which we attribute to the specifics of the material already mentioned.

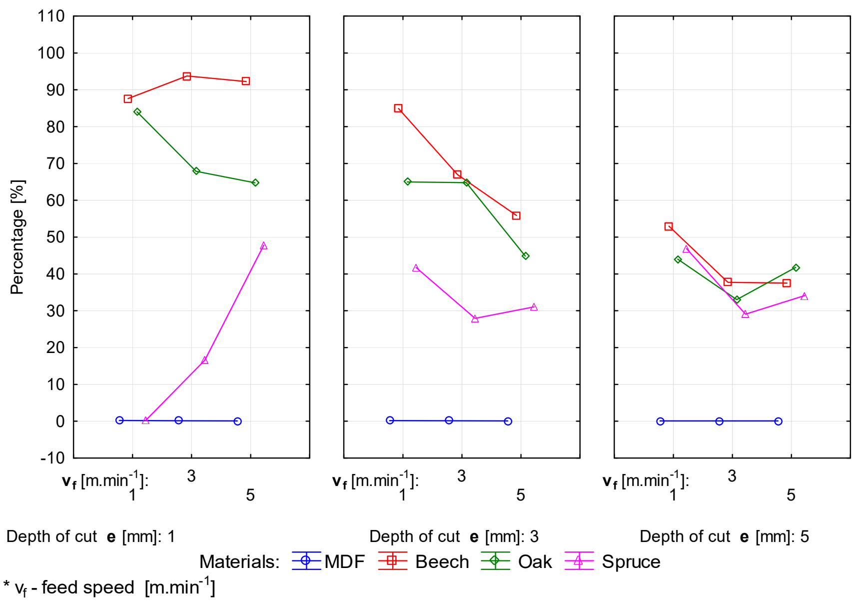

Figure 2. Grain size grade 2 mm.

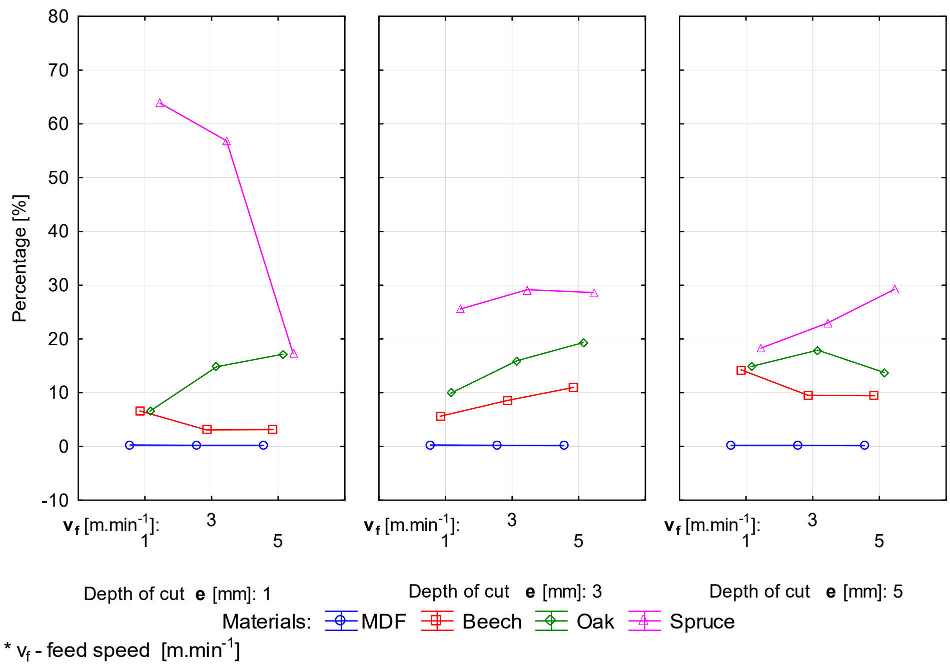

Figure 3. Grain size grade 1 mm.

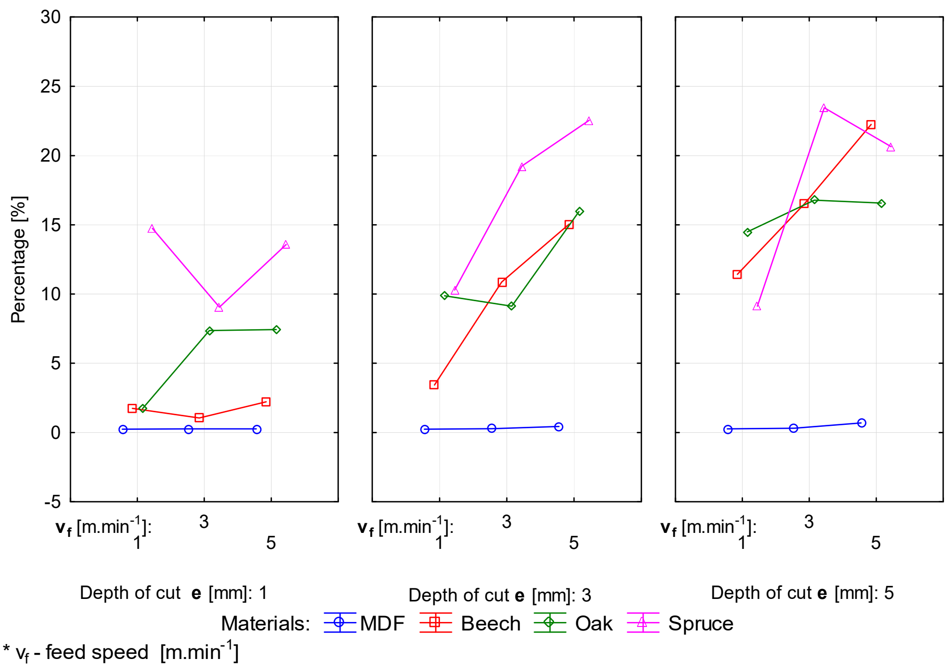

Figure 4. Grain size grade 500 μm.

Graphical representation of the medium-coarse fraction is presented in Figure 5. It became obvious that in the case of MDF panels, the proportion of the 250 μm fraction increased with increasing the depth of cut and feed rate. When processing natural wood, the share of this fraction also increased.

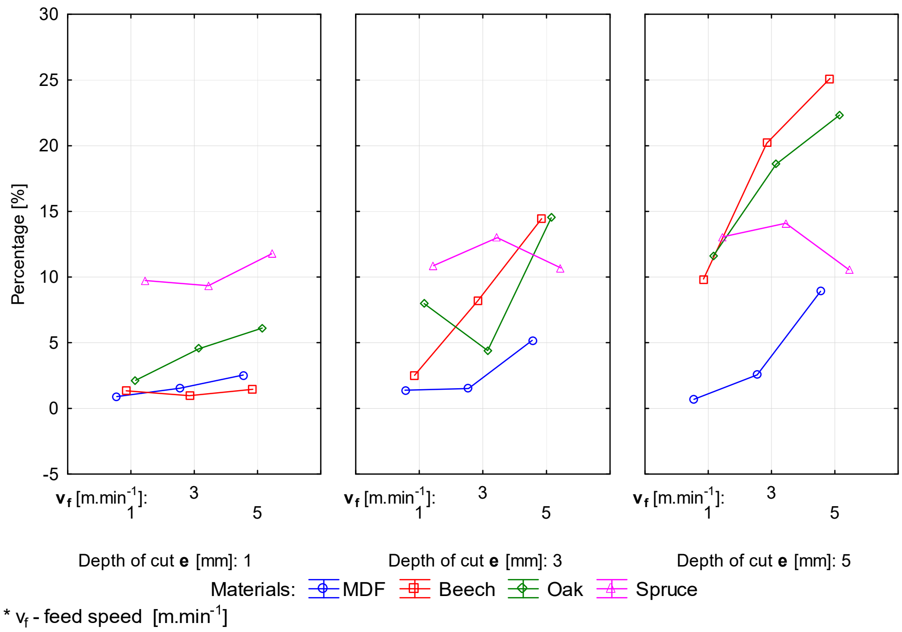

Figure 5. Grain size grade 250 µm.

Fine fractions, presented in Figures 6–9, are of the greatest importance from the point of view of assessing the occupational health risks to workers. Their distribution in machining natural wood was as follows: 0.95% ÷ 16.07% (beech), 5.34% ÷ 15.03% (oak), and 5.47% ÷ 12.67% (spruce), respectively. Noticeably, no particles from the dust fractions below 32 µm were determined. However, the finest dust particles that could be respirable when dispersed in the air are included in the larger sieve fractions. Due to their shape, they cannot pass through sieves with small apertures and join to the larger particles. The weight ratio of particles below 125 µm was represented by the following shares: 0.45% ÷ 4.06% (beech), oak wood 0.92% ÷ 5.86% (oak), and 1.72% ÷ 5.5% (spruce), respectively. The onset part of the nominal particle and the intensity of surface destruction in the particle formation process is the primary source of particles classified as fine fractions (a certain indicator of this destruction is the surface roughness).

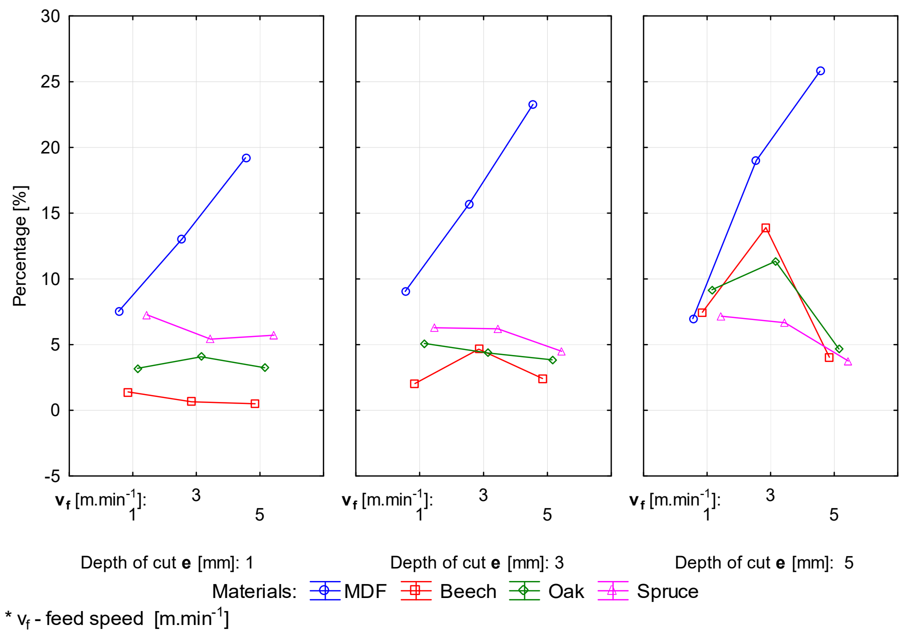

Figure 6. Grain size grade 125 µm.

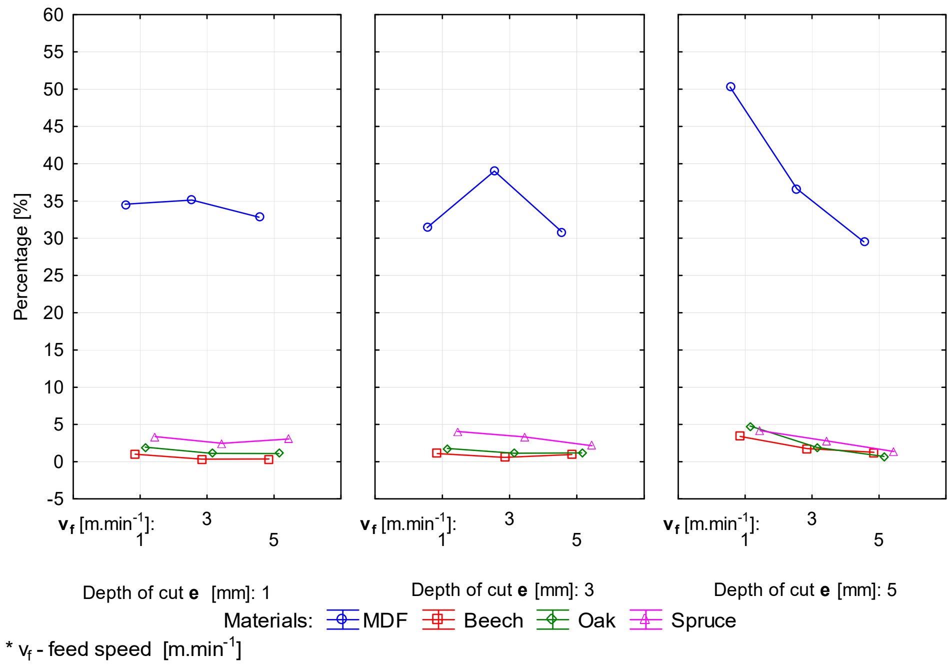

Figure 7. Grain size grade 63 µm.

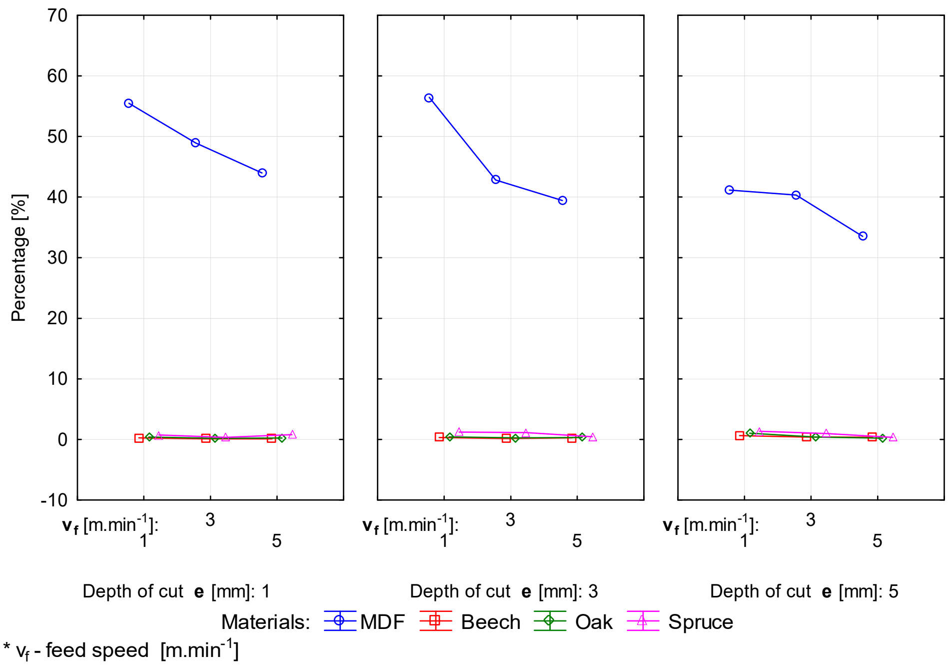

Figure 8. Grain size grade 32 µm.

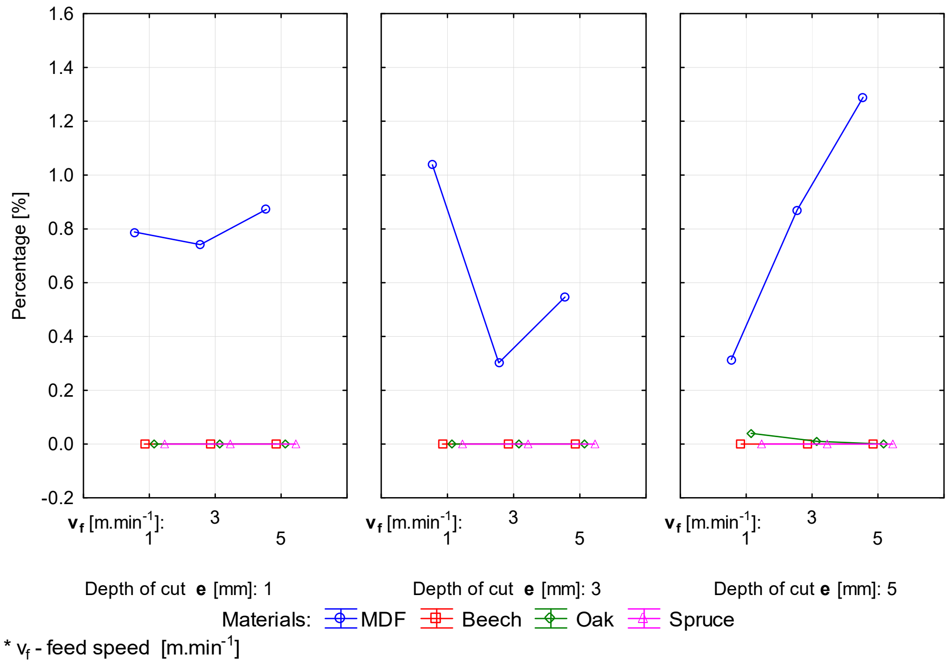

Figure 9. Grain size grade bottom.

The particle size distribution in the case of CNC machining of MDF panels was the opposite. The percentage of the coarse fraction was only 0.27% ÷ 0.51%, and the medium-coarse fractions represented only 1.14% ÷ 9.61%. This means that we can classify the prevailing part of the particles among the fine dust fractions, ranging from 90.1% to 98.72%. Particle fraction 63 ÷ 32 µm was the predominant grain size grade, ranging from 33.5% ÷ 56.44%. The presence of dust particles below 32 µm was also confirmed, which represented 0.3% ÷ 1.29%. The same results were obtained by [43] for four-side molder of MDF. This proves that their content is actually large in this dust [60]. We anticipated such a development based on previously reported results with other MDF machining technologies, but not to such a large extent [4,13,61–63]. This can be attributed to the fibrous structure of the material. The fibers are primarily oriented within their thickness in the particle formation process, and the force ratios in the cutting zone cause the material to disintegrate into fine particles (dust) or fiber clumps.

Markedly, the proportion of fraction trapped on the 125 µm sieve increased in the case of MDF with increasing depth of cut and the increasing feed rate as well. Conversely, the proportion of this fraction decreased with finer particles trapped on the 32 µm sieve with greater depth of cut. The decrease of finer fractions with larger depth of cut was also confirmed by [12]. Other authors [14,30] published in their papers that the proportion of these fractions also increases with increasing feed rate during the machining of particleboard and particles below 125 µm. However, the particleboard has a different structure that may not correspond to the MDF.

It is possible to identify the effect of shear force on the proportion of smaller particles within the fine fractions in terms of the influence of physical and chemical properties of sawn and sanded material, as well as shape, dimensions, sharpness of cutting tools, and technological factors. The feed rate reduction means the decrease of the nominal thickness of the particle and, thus, the particles move between finer fractions. This fact was also confirmed in the works [59,64]. The formation of dust particles can be from all open places of machines as well, especially on the premises of CNC machines as a result of maintenance, repairs, cleaning, inspection, tool change, etc. [42,65–68].

It must be stated in the context of the presented results that the grain size composition of the particles from the milling process is comparable to the grain size composition of the particles from the sanding process, and therefore, the same procedures must be chosen when processing such wood material [69–71].

At the same time, the material mix, which will also include particles from the MDF milling process, will cause considerable complications in the subsequent processing of this material, e.g., in the production of briquettes. It is important to point out that the proportion of fine particles will be not negligible.

The paper is based on standard scientific methodologies for the evaluation of particles from the wood milling process, accepted by scientific capacities, but at the same time, we consider it necessary to mention from the point of view of objectivity and in the context of the stated finding

The sieve analysis method alone cannot be used to determine the content of the finest dust particles. They may not pass through very fine sieves due to the complicated shape of the particles, thus, resulting in possible incomplete data analysis. Therefore, complementary analysis methods should be used for wood dust with a larger dimensional span. Only then is it possible to detect and quantify the content of the finest dust particles and, thus, to estimate the occupational health risks accordingly [30,31].

4. Conclusions

This research demonstrated that a significant percentage of small dust particles with a size below 100 μm is created when machining furniture blanks on CNC machining centers. The comparison of the particle size distributions of wood dust generated during machining of natural wood (beech, oak, and spruce) and MDF panels by a 5-axis CNC machine showed that:

The finest dust fraction was generated during milling of MDF panels, producing particles with predominant grain size ranging from 63 μm to 32 μm. In the case of natural wood, the weight rate of the fine particles was significantly lower than in MDF. The highest content of fine dust particles (below 125 μm) was determined for oak (5.86%), followed by spruce (5.5%), and beech (4.06%), respectively. No clear influence of the feed rate on the fine dust creation was determined. The increased depth of cut resulted in decreased fraction of dust particles with the smallest size.

The formation of fine wood dust particles represents a significant occupational hazard to the health and safety of workers. The results obtained can be used for optimizing the technological programs of CNC milling machines, thus, reducing the occupational exposure to harmful wood dust emissions in the wood-processing industry. High possible depth of cut values should be used to avoid the occupational hazard to the health of woodworkers associated with dustiness.

The improvement of work environment in wood-processing and furniture enterprises by adopting adequate occupational safety and health practices is desirable not only from the perspective of workers but also contributes substantially to labor productivity by enhancing workers' motivation, increasing competitiveness, and promoting economic growth.

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