INTRODUCTION

Thanks to its numerous advantageous properties, wood subjected to thermal treatment has increasingly been used as a suitable material in the production of floors, stairs, ceilings, paneling, elements of building facades, and humid facilities such as saunas and bathrooms. Production of Thermowood© in Europe has been increasing systematically, mainly in Finland and, in recent years, also in Poland. Many significant chemical and physical changes occur in the wood due to thermal processing. Operating with temperature higher than 150°C causes a change in the composition of the cell wall and

Abstract

Objectives: The aim of the study was to determine the effect of parameters of the thermal modification process and machining on the size distribution of dust particles of Scots pine (Pinus sylvestris L.) generated during lengthwise milling.

Method: Unmodified wood and thermally modified wood at temperatures of 130, 160, 190, and 220°C were milled lengthwise at cutting depths of 0.5 and 2 mm. Particle size analysis was done using the sieving method. The content of the finest particles was measured using the laser diffraction method.

Results: The results indicate that at smaller cutting depths, more smaller particles were formed regardless of the wood modification temperature. Thermal treatment of wood does not cause significant differences in the general particle size distribution of dust. However, the content of the finest dust particles depends on the temperature of wood modification. When machined, wood thermally modified at higher temperatures results in the formation of more dust particles that may pose health risks to employees. This is particularly noticeable at a smaller cutting depth.

Conclusion: With the increase of the temperature of the modification, the share of the finest dust particles, which are a potential threat to the health of employees, increases. To reduce dust emissions during milling of thermally modified wood, the highest possible cutting depth should be used.

KEYWORDS

pine wood Pinus sylvestris L., plane milling, thermal modification, wood dust
possible amount. It is possible to carry out processing at different parameters—cutting depth, speed of cutting, and feed speed, but it should not adversely affect the quality of the wooden parts produced.\textsuperscript{17-20}

Therefore, the question arises whether the adverse effect of woodworking in the case of thermally modified wood, such as dust formation, creates worse environment working conditions than in the case of unmodified wood.

The question seems justified, as in literature reports\textsuperscript{21-23} concerning thermally modified wood there is a marked shortage of experimental data concerning the technological properties of thermally modified wood and the impact of machine processing on the working environment. There are only a few publications where fragmentary information about the fractional composition of thermally modified wood dusts can be found, and the research concerns mainly beech and ash, but there is no information on conifers, for example, pine.

\section{2 | THE AIM OF THE STUDY}

Since there is no data on dust creation during the processing of thermally modified softwood, it was decided to determine the effect of parameters of the thermal modification process and machining on the particle size of dust created during the lengthwise milling of Scots pine (\textit{Pinus sylvestris} L.) wood samples. In particular, the content of particles with characteristic dimensions of 4 µm and 10 µm in the created dust was taken into account.

\section{3 | MATERIALS AND METHODS}

\subsection*{3.1 | Wood modification}

The modification process and material for research were prepared in accordance with previously used methodologies.\textsuperscript{24} Experiments were conducted on sapwood of Scots pine (\textit{Pinus sylvestris} L.) cut above breast height from the butt end of a tree aged approx. 100 years. The density of the wood used in the tests determined at an 8% moisture content was 530 kg/m\textsuperscript{3}; the width of annual rings was 2.3 mm; and the share of late wood was 31.6%. From the defect-free sapwood zone, tangentially oriented planks of 20 × 50 × 500 mm (the last dimension measured along the grain) were cut and divided into two sections of 250 mm in length. In this way, pairs of twin samples were produced (producing two identical twin samples). One of the samples was subjected to thermal modification.\textsuperscript{24}

In industrial practice, thermal modification processes of wood are carried out in gaseous media (superheated steam, nitrogen) or in oil. Wood modification was performed under laboratory conditions with the most frequently used method of wood modification being in the atmosphere of superheated
steam, which was run following the ThermoWood® procedure. The diagram of the thermal modification process carried out is shown in Figure 1.24

The modification process was conducted as follows: samples were heated until a temperature of 110°C was reached over their entire volume and this temperature was maintained for 2 hours, until an approx. 1% moisture content was obtained. Next, the temperature was increased until a preset value (130, 160, 190, 220°C) was reached and it was kept constant for 4 hours, that is, the duration of the heating process. From the moment the temperature of 130°C was obtained throughout the sample volume, the modification was run in the atmosphere of superheated steam. After the completion of wood heating at a constant temperature, the heat generator was switched off and, after the temperature of the wood had decreased to 130°C, the steam inflow was shut, and the samples were left in the chamber until the temperature of the wood dropped to an ambient temperature. During the modification process, thermocouples were used to control the temperature of the wood and air in the chamber.24

3.2 | Milling

At the next stage, the radial surfaces of unmodified and thermally modified samples were subjected to longitudinal milling. This was performed using a CNC upper-spindle milling machine type, FLA 16 (Obrusn, Poland). The machining process was carried out using a previously applied methodology.24 The constant machining parameters were as follows: rotational speed of the machine spindle of 18,000 min⁻¹, feed rate of 1 m/min, machining diameter of 16 mm. The tool used was a radial face mill with one cutting knife, with a tool blade of sintered carbide HM with a sharpening angle of 55° (Figure 2). The variable parameter was the cutting depth, that is, 0.5 and 2 mm.24

3.3 | Particle size analysis of dust

A determination of the content of the finest particles in the waste generated during the milling of thermally modified wood was carried out in accordance with the methodology adopted in previous studies of this type.17,25 Dust created during the plane milling of thermally modified pine wood was extracted isokinetically from machines. Then, dust samples of 300 g each were taken from the extractor for particle size analysis. Due to the large range in the size of the dust created during milling, two complementary methods were used to determine dust particle size: sieving and laser light scattering. Sieve analysis only gives a general particle-size distribution without any information considering the finest fractions of dust. Dust particles of inhalable and respirable fractions are much smaller in size than the mesh size of the smallest sieves that can be used to study wood dust. Particle size measurement of the dust taken from milling to determine the content of the smallest particles could not be done by laser particle sizers because there were too many particles whose dimensions were too large and out of range of the laser particle sizers. Therefore, the dust below the sieve of 0.063 mm collected in a bottom holder was taken for measurement and the mass of this dust fraction was considered in the calculations.17,18,25 A set of sieves was used for sieving chips from the plane milling. The sieves were placed on the vibrating holder of a sieving machine, AS 200c (Retsch, Germany), with an adjustable frequency and amplitude of oscillation. Analytical sieves with standardized mesh sizes of 1, 0.5, 0.250, 0.125, 0.063 mm, and bottom collector were arranged top-down in the direction of lowering mesh size. The mass of dust in every size class was determined by weighing what remained on each sieve after sieving on the electronic laboratory scales WPS 510/C/2 (precision of weighing 0.001 g) (Radwag Poland).
Sieving was carried out three times with ca 100 g of dust and the results were determined as the average values of these measurements. Parameters of sieving:

- time of sieving T = 15 min,
- amplitude A = 2 mm.

Then the particle size distributions were determined as follows:

$$Q_3 = \sum_{i=1}^{6} q_{3i} \Delta x_i$$

where $Q_3$ – cumulative distribution by mass, $q_{3i}$ – density distribution by mass, $\Delta x_i$ – width of particle size class, $i$ – number of particle size class.

For the purpose of determining the mass concentration of potentially inhalable and respirable particles in the dust, a laser particle sizer Analysette 22 Microtec Plus (Fritsch, Germany) with a measuring range of 0.08–2000 µm was used. Two particle sizes, 4 and 10 µm, were used to estimate the concentration of very fine particles in the whole mass of the resultant dust. These sizes are the contractual dimensional boundaries between respirable and tracheal dust fractions.\(^{21}\) The mass fractions of these particles were calculated by MaSControl software (Fritsch, Germany) on the basis of the particle size distribution obtained as a result of the particle size measurement.

The calculation of dust fractions in the ranges 0.08–to 4 µm and 4–to 10 µm was done as follows:

$$C_i = C_{s63} \times C_{Li}$$

where $C_i$ – dust fraction in the used size range of the whole mass of waste created, $C_{s63}$ – dust fraction isolated during the sieve analysis in the bottom collector, $C_{Li}$ – mass fractions of the dust in the assumed ranges determined using laser diffraction analysis in the $C_{s63}$ fraction.

The particle size analysis of chips formed during milling was performed in accordance with the following standards, ISO 3310-1:1990\(^a\) and ISO 2591-1:1998\(^b\), and measurements of the content of the finest particles were carried out using a laser particle size meter in accordance with ISO 13320:2009\(^c\).

4 | RESULTS

The graphic presentation of the measurement results for the cumulative distribution of dust created during the milling of unmodified wood in the function of particle size for the cutting depths 0.5 and 2 mm shows a difference between the distribution curves (Figure 3A). The presented data indicate that larger amounts of smaller particles were created at a smaller cutting depth.

The same differences were observed in the case of waste from thermally modified wood (Figure 3B–E). The next graph shows the dust fractions isolated during the sieving analysis in the bottom collector of the sieving machine (Figure 4). The graph shows the smallest fraction, that is, the amount of waste sifted through the smallest meshed sieve. The modification process resulted in the generation of the finest chip fraction. The higher the temperature of wood modification, the finer the produced fractions were. Cutting depth is also important in this case. At a shallower cutting depth, finer waste dust particles were observed.

The influence of the wood modification temperature on the content of the finest particles is shown in Figure 5. The results show the effect of temperature, as each increase in the temperature of wood modification resulted in an increase in the content of the finest particles in dust produced during milling. For dust particles in the size range of 4–10 µm generated during milling at a cutting depth
FIGURE 3  Cumulative distribution of dust created during milling the pine wood – (A) unmodified; (B) thermally modified at 130°C; (C) thermally modified at 160°C; (D) thermally modified at 190°C; (E) thermally modified at 220°C
of 0.5 mm, each temperature increase of 30°C caused a twofold increase in the content of these particles. In the case of unmodified wood waste, the content of the finest particles was definitely smaller compared to waste from modified wood.

Regardless of the wood modification temperature, fine dust levels were markedly greater for a cutting depth of 0.5 mm compared to a cutting depth of 2 mm.

5 | DISCUSSION

Studies have shown that, in addition to the effect of processing parameters, in this case the cutting depth, the content of fine dust particles with regard to thermally modified wood is also affected by the wood modification temperature.

However, the results of the sieve analysis presented indicate a low variability in waste from thermally modified wood at different temperatures, also compared to waste from unmodified wood. Comparison of the distribution curves shown in Figure 3 for unmodified and modified wood at different temperatures shows that subjecting wood to thermal modification caused no significant differences in the particle size distribution obtained using the sieve analysis method compared to unmodified wood; however, the dust from modified wood is slightly finer. Considering the cutting depth during milling of both unmodified and thermally modified wood, it was found that, with a decrease in cutting depth, chips of smaller sizes were produced regardless of the wood modification temperature (Figure 3). Due to the fact that the smallest mesh size used in the sieve analysis, that is, 0.063, was many times larger than the size of particles that can penetrate the human respiratory tract, differences in their content depending on the intensity of thermal treatment could only be determined using the laser diffraction method, by which the smallest particles can be detected in the whole dust mass. Similarly, Dzurenda and Orłowski 21 studied ash wood sawdust and Dzurenda et al 22 analyzed oak wood sawdust at different feed speeds and concluded that thermally modified sawdust is also finer. However, the comparison of data from the papers of these authors regarding ash and oak wood sawdust which passes through the sieve mesh size of 0.063 µm and dust from the milling of modified pine wood (Figure 4) shows that sawdust is coarser. Nevertheless, these authors found no particles of less than 0.032 µm in diameter, that is, the smallest mesh size used in their analysis. This was
due to the limitation of sieve analysis. Wood dust particles are fibrous, and particle size analysis requires a combined procedure of complementary methods.\textsuperscript{26}

On the other hand, Hlásková et al.\textsuperscript{23} observed different content of the fine dust particles in sawdust generated during the sawing of beech wood modified by various technologies. The authors also used the laser diffraction method for dust particle characterization. Therefore, wood modification technology or modification process parameters are significant for dust production during the mechanical processing of modified wood. Hlásková et al.\textsuperscript{23} have found that there are more particles with the characteristic sizes below 4 \( \mu \)m and 10 \( \mu \)m in sawdust from modified wood. It is also finer (excluding Lignamon) compared to the dust from the milling of modified pine wood (Figure 5).

Particles of such sizes may constitute the thoracic and respirable fractions after being dispersed in the air. Since wood dust is a carcinogenic substance, future developments should take into account the fact that much greater amounts of fine dust are generated during the processing of thermally modified wood. Therefore, specially adapted processing parameters should be used to limit the generation of the finest dust particles. Thus, in the case of thermally modified wood, higher cutting depths should be used. The values of feed speed and cutting speed can be selected accordingly to produce coarser chips. Nevertheless, this should not result in a deterioration of machining quality.

It should be considered that the carcinogenicity of dust from thermally modified wood is at least the same as that of dust from unmodified wood, although there is no comprehensive data on the influence of thermal wood modification on the potential harmfulness of dust.\textsuperscript{13} Employees are exposed to a greater health hazard when machining thermally modified wood because greater amounts of fine dust are produced under the same processing conditions than in the case of unmodified wood.

6 CONCLUSION

The thermal modification process affects the content of fine dust particles in the waste. As the temperature of the modification increases, the fine particles in the waste, which are a health risk, increase. The cutting depth also plays a significant role in the fractional composition of the chips produced during machining. Analysis of the obtained results indicates that the increase in cutting depth causes the formation of larger size waste. At lower cutting depths, more fine waste (dust) is created, and an increase in cutting depth creates larger waste. However, as the temperature of the modification increases, the share of the finest particles (dusts) that pose health risks increases. To reduce dust emissions during the milling of thermally modified wood, the highest possible cutting depth should be used.

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DISCLOSURE

Approval of the research protocol: N/A. Informed consent: N/A. Registry and the registration no. of the study/trial: N/A. Animal studies: N/A. Conflict of interest: The authors declare there are no potential sources of a conflict of interest. The paper does not concern research on humans or animals.

AUTHOR CONTRIBUTIONS

Magdalena Piernik: data analysis, text preparation, wood modification realization; Tomasz Rogoziński: data analysis, text preparation, particle size analysis; Andrzej Krauss: data analysis, text preparation, conception of the paper; Grzegorz Pinkowski: data analysis, wood milling realization.

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ENDNOTES

\( ^a \) ISO 3310-1:1990: Test sieves – Technical requirements and testing – Part 1: Test sieves of metal wire cloth.
\( ^b \) ISO 2591-1:1998 Test sieving – Part 1: Methods using test sieves of woven wire cloth and perforated metal plate.
\( ^c \) ISO 13320: 2009. Particle size analysis – Laser diffraction methods.

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