Effect of Thermal Modification of Oak Wood on Sawdust Granularity

Utjecaj termičke modifikacije hrastovine na granulometrijski sastav piljevine

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ABSTRACT • *This paper presents the results of granulometric analyses of sawdust of thermally modified oak wood and unmodified oak wood sawed on narrow-kerf sash gang saw. Sawdust of dry thermally modified oak, produced during the sawing process on the frame sawing machine PRW 15–M with the feed speed of 0.36 and 1.67 m·min^{-1}, consists of chip granularity in the range from 0.0412 mm to 3.6 mm, whereas the unmodified oak wood sawdust consists of chips in the granularity range from 0.0448 mm to 12.1 mm. In both cases polydispersive fibrils with a strong extension in one dimension were observed. It can be concluded that thermally modified oak sawdust is finer, with a distinct larger participation of the fraction in the granularity range a = 125–500 µm and a slightly increased share of the fraction in the range a = 32–125 µm.*

Key words: *oak wood sawdust, thermal modification, frame sawing machine, granulometric analysis, granularity*

SAŽETAK • *U radu su izneseni rezultati granulometrijske analize piljevine termički modificirane i nemodificirane hrastovine. Uzorci piljevine dobiveni su piljenjem modificiranoga i nemodificiranog drva pilom jarmačom male širine propiljka. Piljevina suhe termički modificirane hrastovine, dobivena u procesu piljenja jarmačom PRW 15–M posmičnom brzinom 0,36 i 1,67 m·min^{-1} sadržava drvne čestice veličine 0,0412 – 3,6 mm a piljevina nemodificirane hrastovine sadržava čestice veličine 0,0448 – 12,1 mm. Može se zaključiti da se piljevina termički modificiranog drva sastoji od sitnijih čestica, sa znatno većim udjelom frakcije čestica veličine a = 125–500 µm i nešto većim udjelom frakcije čestica veličine a = 32–125 µm.*

Ključne riječi: *hrastova piljevina, termički modificirano drvo, pila jarmača, granulometrijska analiza, veličina čestica*

1 INTRODUCTION
1. UVOD

During the sawing process of wood, chip sawdust is produced together with the main product. The shape, size and amount of chips depend on the form, physical and mechanical properties of sawed wood as well as on the shape, dimensions, sharpness of the cutting blade, and technical and technological conditions of the sawing process (Prokeš, 1978; Goglia, 1994; Lisičan *et al.*, 1996; Wasielewski, 1999, Orłowski, 2003, Beljo Lučić *et al.*, 2005; Očkajova *et al.*, 2006; Kopecký and Rousek, 2007; Klement and Detvaj, 2007; Dzurenda, 2007).

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Sawdust is characterized as poly-dispersion bulk material consisting of coarse and medium coarse fractions (Hejma, 1981), i.e. bulk material with grain size of more than 0.3 mm, while the share of fine fractions with smaller chip size is not excluded. According to classifying parameters of bulk material stated in the standard STN 26 0070, sawdust is classified as B-45UX, e.g. bulk material of fine granularity (0.5–3.5 mm), hygroscopic, low crisp and abrasive material with a tendency to crowding.

Utilization of sawdust as a secondary raw material is miscellaneous. For example, sawdust is one of the base materials used for production of agglomerated chip materials and for chemical processing of wood. It is a valuable raw material for energy exploitation by direct combustion, and eventually for production of dimensionally and energetically homogenized fuel (briquettes and pellets).

The increasing interest in sawdust, as a secondary raw material, in the last years, requires a proper specification of its physical properties as follows: granularity, geometric shapes and size of sawdust chips. The aim of this work is to analyze the effect of the thermal treatment of oak wood on sawdust granularity during the sawing process conducted on the frame sawing machine PRW15–M.

2 MATERIAL AND METHODS
2. MATERIJALI I METODE

Thermal modification of oak (*Quercus robur* L.) was performed in the overheated steam in a high temperature steam dry kiln PW-10 (Fig. 1, f. Hamech, PL) with ThermoWood technology under conditions presented in Fig. 2.

Samples of dry oak (native, unmodified) sawdust and dry sawdust of thermally modified oak were taken for granulometric analyses from the exhaust pipe of frame sawing machine PRW 15–M through the isokinetic probe of Gravimetric equipment, type MU 5 – OT, in accordance with STN ISO 9096:1997 (Determination of concentration and mass flow rate of particulate material

Figure 1 High temperature steam dry kiln PW-10
Slika 1. Visokotemperaturna parna sušionica PW-10

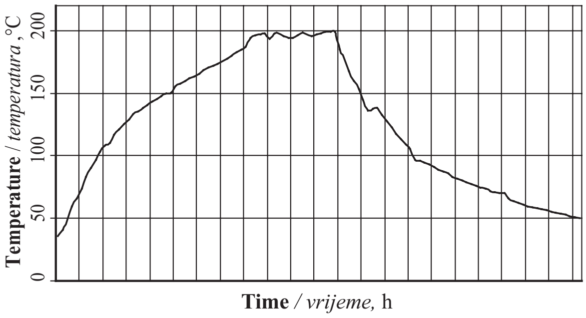


Figure 2 Thermal modification conditions of oak wood samples
Slika 2. Uvjeti termičke modifikacije hrastovih uzoraka

in gas-carrying ducts.) in sawing modified and unmodified oak wood. Square timber blocks, with dimensions 59.5×59.5×500 mm after planning, were sawed with feed speed v_1 = 0.36 m·min^{-1} and v_2 = 1.67 m·min^{-1} on the frame sawing machine PRW 15–M (Tab. 1) in the laboratory of the Gdansk University of Technology. Moisture content of oak sawdust W_{OAK} = 8.5% and thermally modified oak wood sawdust W_{OAK-M} = 8.7% were determined by the weight method. Technical and technological conditions of sawing are shown in Table 1.

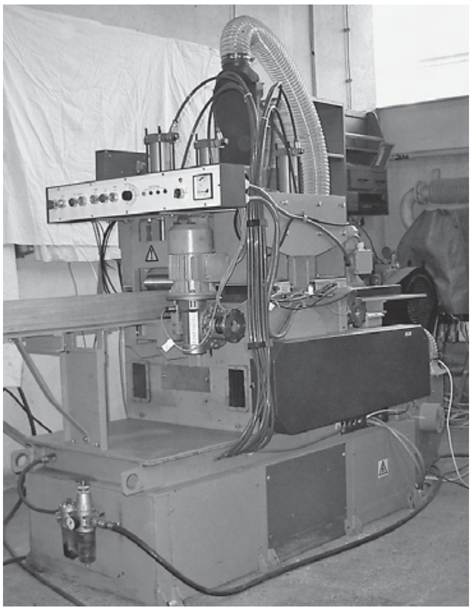
The basic granulometric analyses were carried out by sieving, which means by screening of sawdust on a set of sieves with mesh sizes: 2 mm, 1 mm, 0.50 mm, 0.25 mm, 0.125 mm, 0.080 mm, 0.063 mm and 0.032 mm, during the time τ = 15 min on an automatic vibration sieving machine AS 200 (f. RETSCH). The weights of fractions on sieves were determined on the laboratory balance EP 200 (f. BOSCH) with 0.001 g accuracy. The granulometric analysis of sawdust of thermally modified and unmodified wood was made on 3 samples.

For the purpose of specifying the size of the smallest particles of fine fraction of dry oak sawdust, a microscopic analysis of granules of fraction of dry oak sawdust was done. The additional analysis of dry oak sawdust was carried out by an optical method – analysis of an image taken with the microscope Nikon Optiphot–2 with the objective Nikon 4× in the Biometric Laboratory FLD MZLU Brno. Granules of sawdust were scanned by 3D TV CCD camera HITACHI HV-C20 (RGB 752×582 pixels), with horizontal resolution 700 TV lines, and evaluated by the software LUCIA-G 4.0 (Laboratory Universal Computer Image Analysis), installed on a PC with the processor Pentium 90 (RAM 32 MB) with the graphic card VGA Matrox Magic under the operation system Windows NT 4.0 Workstation. The program of image analysis LUCIA-G enables the identification of individual particles of disintegrated wood material, quantitative determination of individual particles situated in the analysed image and basic information such as: width and length of particles, circularity expressing the measure of deviation of projection of a given chip shape from the projection of the shape of a circle according to the relation:

$$\psi = \frac{4 \cdot \pi \cdot S}{O^2} \qquad (1)$$

where: S – surface of particle (*površina čestice*), m^2
O – circumference of particle (*opseg čestice*), m

Table 1 Technical and technological conditions of sawing during sampling of sawdust
Tablica 1. Tehnički i tehnološki uvjeti piljenja pri uzimanju uzoraka piljevine



Narrow-kerf frame sawing machine PRW 15–M *Pila jarmača male širine propiljka PRW 15–M*		
Span of the saw frame *Svijetli otvor jarmače*	mm	170
Stroke of the saw sash *Duljina stapaja*	mm	160
Max. height of sawn material *Maksimalna visina piljenog materijala*	mm	150
Min. height of sawn material *Minimalna visina piljenog materijala*	mm	30
Min. length of sawn material *Minimalna duljina piljenog materijala*	mm	350
Number of saw blades in the gang during tests *Broj pila upetih u okvir tijekom piljenja*	-	5
Overall set (kerf) of saw blades *Širina propiljka*	mm	2
Cutting edge material *Materijal rezne oštrice*	stelit	
Feed speed / *Posmična brzina*	$m \cdot min^{-1}$	$v_1 = 0.36$ $v_2 = 1.67$

3 RESULTS AND DISCUSSION
3. REZULTATI I DISKUSIJA

Results of the sieve analyses of granulometric composition of dry sawdust of unmodified and thermally modified oak are presented in Tables 2 to 5.

The largest and smallest dimensions of particles recognized in the dry oak sawdust from natural (unmodified) and thermally modified oak wood obtained during sawing on the narrow-kerf frame sawing machine PRW15–M M with feed speed of $v_1 = 0.36$ $m \cdot min^{-1}$ are shown in table 3.

Results of the sieve analyses granulometric composition of dry sawdust of unmodified and thermally modified oak with feed speed of $v_2 = 1.67$ $m \cdot min^{-1}$ are presented in table 4.

The largest and smallest sizes of particles recognized in the dry oak sawdust from natural (unmodified) and thermally modified oak wood obtained during sawing on the narrow-kerf frame sawing machine PRW 15–M with feed speed of $v_2 = 1.67$ $m \cdot min^{-1}$ are shown in Table 5.

Based on the analysis carried out, it can be concluded that the sawdust of dry thermally modified oak produced during the sawing process on the frame sawing machine PRW 15–M with feed speed of $v_1 = 0.36$ $m \cdot min^{-1}$ and $v_2 = 1.67$ $m \cdot min^{-1}$ consists of chip granularity in the range $a = 0.0412 – 3.6$ mm, whereas the unmodified oak wood sawdust consists of chips in the granularity range $a = 0.0448 – 12.1$ mm.

The analysis of size and shape of particles of dry sawdust of both unmodified and thermally modified oak shows that chips of coarse and medium coarse fractions fall into the category of polydispersive fibrils with a strong extension in one dimension. Chips of fine fraction are within the category of isometric particles, i.e. particles with the same dimensions in all three dimensions. The above statement is the result of the fact

Table 2 Granulometric composition of dry oak sawdust from frame saw PRW 15–M with feed speed $v_1 = 0.36$ $m \cdot min^{-1}$
Tablica 2. Granulometrijski sastav suhe hrastove piljevine dobivene piljenjem na jarmači PRW 15–M posmičnom brzinom $v_1 = 0,36$ $m \cdot min^{-1}$

Measures of sieve meshes *Veličina otvora sita* mm	**Mark of fraction** *Oznaka frakcije*	**Representation of fractions in dry oak sawdust, %** *Udjeli frakcija u suhoj hrastovoj piljevini, %*							
		Unmodified wood *Nemodificirano drvo*				Thermally modified wood *Termički modificirano drvo*			
		sample 1 *uzorak 1.*	sample 2 *uzorak 2.*	sample 3 *uzorak 3.*	average *prosjek*	sample 1 *uzorak 1.*	sample 2 *uzorak 2.*	sample 3 *uzorak 3.*	average *prosjek*
2.000	coarse	0.80	1.54	1.68	1.34	2.08	2.82	2.87	2.59
1.000		3.64	4.83	4.17	4.21	3.08	3.42	3.92	3.47
0.500	medium coarse	36.48	37.15	36.84	36.82	19.85	20.78	21.37	20.67
0.250		41.08	39.12	38.38	39.53	47.93	46.29	45.36	46.53
0.125	fine	15.46	14.99	15.89	15.45	23.11	21.76	21.61	22.16
0.080		1.87	1.68	2.20	1.92	3.02	3.28	3.41	3.23
0.063		0.56	0.59	0.71	0.62	0.71	1.14	0.99	0.95
0.032		0.10	0.10	0.13	0.11	0.22	0.51	0.47	0.40
< 0.032		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Table 3 Areal dimensions of the largest and smallest chips in examined oak sawdust with feed speed v_1 = 0.36 m·min^{-1}
Tablica 3. Dimenzije površine najvećih i najmanjih čestica u piljevini nemodificirane hrastovine dobivene piljenjem posmičnom brzinom v_1 = 0,36 m·min^{-1}

Wood / *Drvo*	**Dimensions of maximum chips, mm** *Dimenzije najvećih čestica, mm*			**Dimensions of minimum chips, µm** *Dimenzije najmanjih čestica, µm*		
	sample 1 *uzorak 1.*	sample 2 *uzorak 2.*	sample 3 *uzorak 3.*	sample 1 *uzorak 1.*	sample 2 *uzorak 2.*	sample 3 *uzorak 3.*
Unmodified oak *Nemodificirana hrastovina*	3.2 × 8.8 2.9 × 7.7 1.8 × 5.6	4.3 × 9.4 3.9 × 8.8 2.7 × 7.9	3.2 × 9.6 3.3 × 8.6 2.6 × 7.8	37.1 × 43.6 37.6 × 45.3 40.2 × 46.8	39.5 × 43.6 42.8 × 44.2 43.2 × 45.2	40.7 × 44.3 42.6 × 44.9 44.7 × 45.2
Thermally modified oak *Termički modificirana hrastovina*	2.2 × 4.5 1.8 × 3.9 1.7 × 3.6	1.3 × 3.6 1.1 × 3.7 0.8 × 2.3	2.7 × 3.9 1.2 × 3.5 1.9 × 2.9	36.1 × 41.2 37.4 × 42.6 41.3 × 44.5	41.6 × 41.5 39.9 × 42.3 37.8 × 46.4	40.8 × 42.2 41.1 × 42.8 39.1 × 43.3

Table 4. Granulometric composition of dry oak sawdust from frame saw PRW 15–M with feed speed v_2 = 1.67 m·min^{-1}
Tablica 4. Granulometrijski sastav suhe hrastove piljevine dobivene piljenjem na jarmači PRW 15–M posmičnom brzinom v_2 = 1,67 m·min^{-1}

Measures of sieve meshes *Veličina otvora sita* mm	**Type of fraction** *Oznaka frakcije*	**Representation of the fractions in the dry oak sawdust, %** *Udjeli frakcija u suhoj hrastovoj piljevini, %*							
		Unmodified wood *Nemodificirano drvo*				Thermally modified wood *Termički modificirano drvo*			
		sample 1 *uzorak 1.*	sample 2 *uzorak 2.*	sample 3 *uzorak 3.*	average *prosjek*	sample 1 *uzorak 1.*	sample 2 *uzorak 2.*	sample 3 *uzorak 3.*	average *prosjek*
2.000	coarse	1.52	2.56	1.89	1.99	1.28	3.58	0.87	1.91
1.000		8.63	7.23	8.05	7.97	2.76	3.06	2.92	2.91
0.500	medium coarse	41.85	35.03	38.74	38.54	23.49	26.35	24.73	24.86
0.250		35.24	38.67	36.15	36.69	51.05	45.54	48.39	48.33
0.125	fine	10.57	12.60	11.99	11.72	18.05	16.52	18.12	17.56
0.080		1.51	2.84	2.20	2.18	2.37	3.17	3.30	2.95
0.063		0.48	0.89	0.77	0.71	0.67	1.07	0.99	0.91
0.032		0.20	0,18	0.21	0.20	0.31	0.72	0.68	0.57
< 0.032		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Table 5 Areal dimensions of the largest and smallest chips in tested oak sawdust with feed speed v_2 = 1.67 m·min^{-1}
Tablica 5. Dimenzije najvećih i najmanjih čestica u piljevini nemodificirane hrastovine dobivene piljenjem posmičnom brzinom v_2 = 1,67 m·min^{-1}

Wood / *Drvo*	**Dimensions of maximum chips, mm** *Dimenzije najvećih čestica, mm*			**Dimensions of minimum chips, µm** *Dimenzije najmanjih čestica, µm*		
	sample 1 *uzorak 1.*	sample 2 *uzorak 2.*	sample 3 *uzorak 3.*	sample 1 *uzorak 1.*	sample 2 *uzorak 2.*	sample 3 *uzorak 3.*
Unmodified oak *Nemodificirana hrastovina*	3.3×9.8 1.4×4.2 0.8×3.9	4.2×12.1 2.8×9.0 2.1×4.3	3.1×11.2 4.3×8.4 2.1×3.8	44.7×48.8 47.6×52.3 50.1×57.3	43.7×44.8 46.8×48.3 49.9×51.6	44.7×45.2 46.6×47.3 47.7×49.3
Thermally modified oak *Termički modificirana hrastovina*	2.3×4.6 1.4×3.5 0.8×2.9	1.1×3.6 1.0×2.8 0.7×2.1	1.7×3.9 1.2×3.3 0.7×2.7	45.2×45.0 46.2×46.8 47.3×47.5	44.8×44.8 45.9×46.3 46.8×47.1	44.3×44.7 46.1×47.2 47.1×48.3

that the planar projection of chips determined by an optical method has the shape of a square, or the value of circularity in the interval of Ψ = 0.7–1.0 provided that the third dimension of freely scattered three-dimensional objects on a horizontal pad is smaller than their largest dimension.

The same information on the shape of particles was determined by the analysis of pine sawdust particles produced during the process of dry pine sawing on the frame sawing machine PRW15–M with feed speed v = 0.5 m·min^{-1} and 1.5 m·min^{-1} (Dzurenda *et al.,* 2006).

On the bassis of experimental results of granulometric compositions of dry oak sawdust of unmodified and thermally modified oak wood, granularity courses of sawdust were elaborated (Fig. 3 and Fig. 4).

Residue courses (Fig. 3) and also the results of sieve analysis of sawdust from the sawing processes of unmodified and modified oak wood (Table 2 and 4) show that sawdust produced during the sawing process of dry thermally modified oak is finer (course A is shifted to the left, Fig. 3) than sawdust from unmodified oak. In the sawdust of thermally modified wood the share of both moderate coarse fractions in the range a = 125–500 µm has sharply increased. Furthermore, there is an increase of the share of fine fraction in the range of granularity a = 32–125 µm at the expense of the fraction a = 0.5–2.0

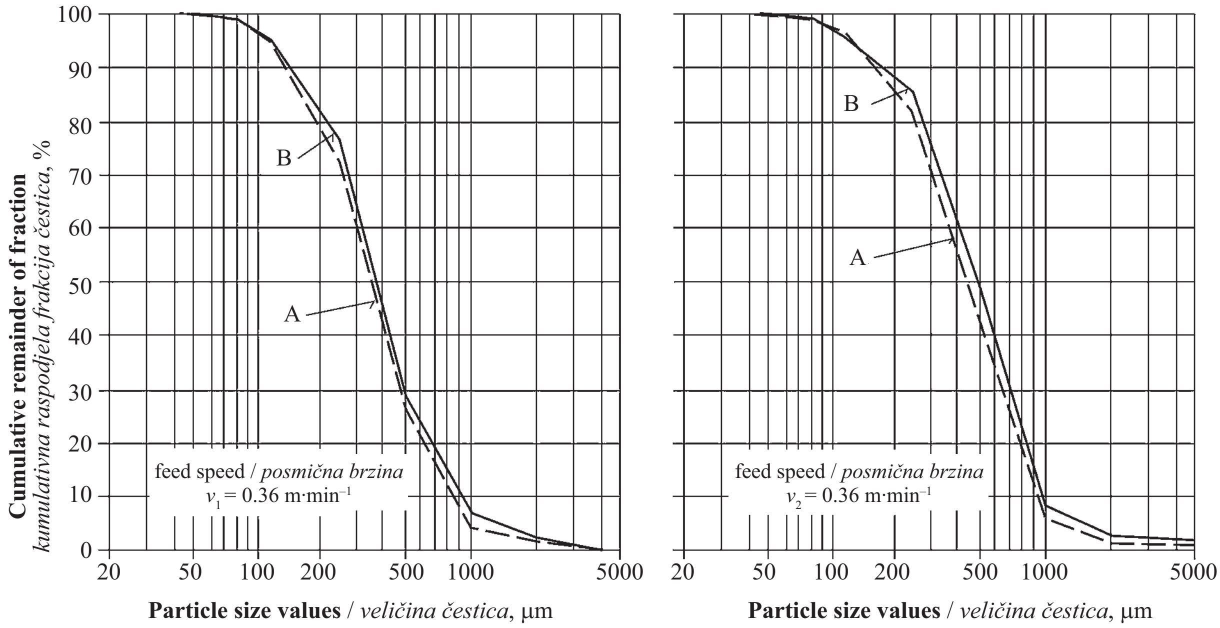


Figure 3 Residue courses of dry sawdust produced in sawing on the frame sawing machine PRW15–M, where: A – thermally modified oak, B – unmodified oak
Slika 3. Kumulativna raspodjela veličina čestica suhe piljevine dobivene piljenjem jarmačom PRW15–M (A – termički modificirinao drvo, B – nemodificirano drvo)

mm. This fact can be attributed to the increased fragility of thermally modified oak wood (Mayes and Oksanen, 2002; Reinprecht and Vidholdová, 2008). Similar results, i.e. refinement of chip granularity, were observed during milling process of thermally modified beech wood (Beljo Lučić *et al*, 2009) and during abrasing processes of acacia thermowood (Wieloch *et al*, 2009).

The determination of lower interval limit of sawdust granularity $a_{\min}$ = 41.2 μm from sawing of thermically modified oak wood on a frame sawing machine PRW M–15 allows the characterization of dry oak sawdust from thermically modified and unmodified wood as a potential source of airborne dust in the working environment. The calculation of isometric chips of fine fraction of sawdust with the shape of a cube to aerodynamic diameter D_r of airborne particles of dust with the shape of a sphere with density ρ = 1000 kg·m^{-3}, in accordance with EN 481:1993, is as follows:

$$D_{r-\min} = \sqrt[3]{\frac{6}{\pi} a_{\min}^3} \cdot \sqrt{\frac{\rho_m}{1000}}$$

$$D_{r-\min} = \sqrt[3]{\frac{6}{\pi}(41.2)^3} \cdot \sqrt{\frac{650}{1000}} = 44.21\ \mu m \qquad (2)$$

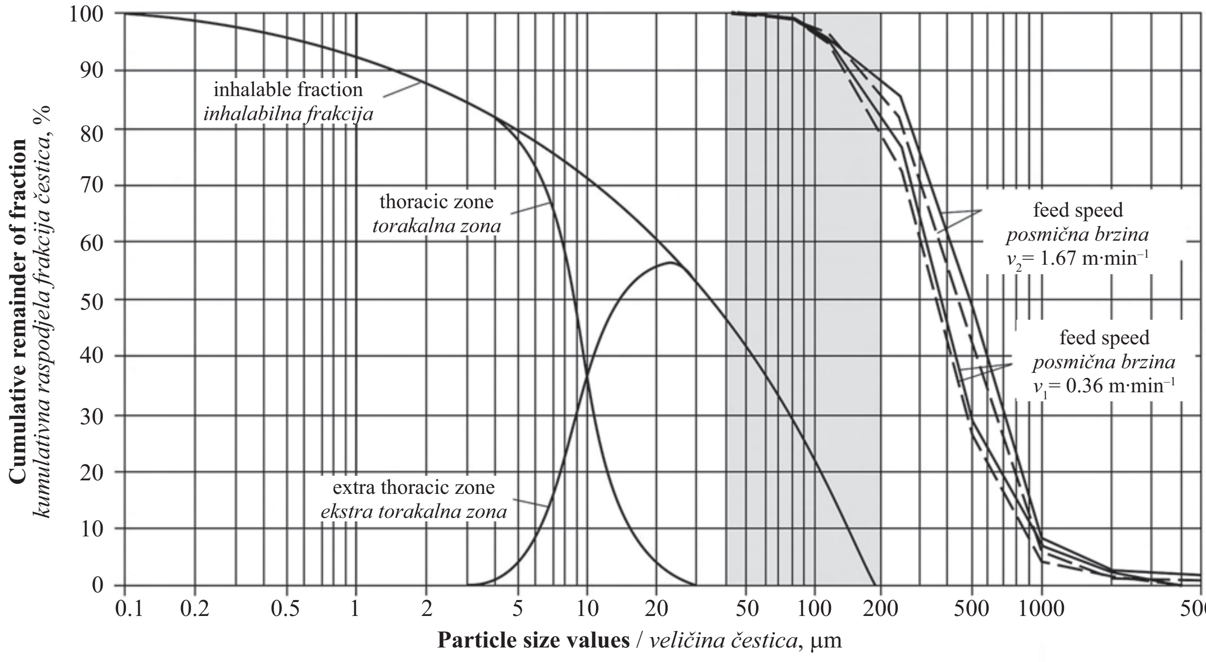


Figure 4 Effect of sawing oak wood (modified and unmodified) on the sash gang saw PRW15–M on pollution of the working environment with inhalable fractions
Slika 4. Utjecaj procesa piljenja hrastovine (nemodificirane i termički modificirane) pilom jarmačom na onečišćenje radnog okoliša inhalabilnim česticama

This result allows us to exclude processes of sawing of thermically modified oak wood as well as unmodified oak wood on a frame sawing machine PRW 15–M from the category of technological processes polluting the working environment with particles of thoracic fraction of airborne dust $D_r \leq 30$ μm, which means particles that could penetrate behind larynx if inhaled. However, in case of inefficient air transport of sawdust from the frame sawing machine PRW 15–M, extrathoracic fractions of airborne dust with the size D_r = 44.21 μm to 200 μm are produced into the working environment, as shown in Fig. 4.

4 CONCLUSIONS
4. ZAKLJUČCI

Based on the analysis carried out, it can be concluded that the sawdust of dry thermally modified oak produced during the sawing process on the frame sawing machine PRW 15–M with feed speed v_1 = 0.36 m·min^{-1} and v_2 = 1.67 m·min^{-1} consists of chip granularity in the range a = 0.0412 – 3.6 mm, whereas the unmodified oak wood sawdust consists of chips in the granularity range a = 0.0448 – 12.1 mm. In both cases polydispersive fibrils with a strong extension in one dimension were observed.

In terms of the shape of particles, chips of coarse and medium coarse fractions fall into the category of fibril bulk materials, whereas chips of the fine fraction are in the category of isometric particles.

Thermally modified oak sawdust is finer, with a distinctly larger share of medium coarse and fine fractions in the granularity range a = 125–500 μm and a slightly increased share of the fraction in the range a = 32–125 μm at the expense of the fraction a = 0.5–2.0 mm.

Dry oak sawdust, as well as dry oak sawdust thermally modified by ThermoWood technology produced in the process of sawing on a frame sawing machine PRW 15–M does not contain dust particles of thoracic fraction of airborne dust.

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