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Influence of Thermal Treatment on the Mechanical Properties of Pinewood

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The influence of thermal treatment on the compression strength and static bending resistance of pinewood has been investigated. The thermal treatment conditions close to real technological regimes were selected. The samples were dried at 60, 80, 100 and 120 °C for 24, 48, 72 and 96 hours. Linear dimensions of the samples were 20 mm × 20 mm in cross section and length 30 mm for compression and 300 mm for bending test. It was shown that the thermal treatment increases compression resistance parallel to the grain, while compression perpendicular to the grain and bending strength decreases. The increase of thermal treatment regimes decreases bending strength of pinewood. Average width of annual rings also influences mechanical properties; larger width of annual rings increases compression strength perpendicular to the grain in radial direction. Static bending at these conditions reaches the lowest values. The character of dependencies between static bending strength and width of annual rings does not change under thermal treatment.
Keywords: pinewood, thermal treatment, compression, static bending, annual rings.

1. INTRODUCTION

Due to the unique properties and relatively high natural resources wood is widely used in various fields. Worldwide the annual usage of wood is about 5 billions m^3, in that time for cement that is 1.9 billions m^3, for steel is 0.11, for plastics is 0.18 and aluminium 0.01 billion m^3 per year [1, 2]. Independently on the replantation, the wood recourses decrease, due to increase of wood usage. In order to increase rational exploitation of natural resources, wood is refined in different modes. One of modes is thermal treatment using heat and gas or special liquids. During this treatment the required physical, mechanical and exploitation properties are obtained [3, 4].

In dependence on the required final result wood can be heated or dried. In order to increase durability and stability of dimensions wood is heated at temperature of 180 °C – 230 °C without chemical additives. Disadvantage of this treatment is decrease of mechanical properties and colour changes [5 – 7].

To leave wood properties unchanged, wood is dried. Drying temperature depends on the wood type, assortment measures, type of drying chamber and drying regimes. Usually pinewood is dried at 55 °C – 130 °C temperature. For drying wood pieces of 22 mm – 60 mm in thickness using low temperature (soft) regimes, initial drying temperature is 55 °C – 57 °C and final drying temperature is about 75 °C – 77 °C. For normal drying regimes, initial temperature is 71 °C – 83 °C and final temperature is 94 °C – 110 °C. Then using intensified regimes initial drying temperature is 83 °C – 94 °C and final is 110 °C – 125 °C. Soft drying regimes do not influence on the colour, physical and mechanical wood properties. Normally, drying regimes influence on the wood colour and intensified regimes decrease wood shear strength about 15 % – 20 % [1, 5].

High temperature drying regimes for pinewood 22 mm – 60 mm in thickness was drying temperatures from 120 °C to 130 °C. This drying mode results in decrease of compression, bending and tensile strength of about 8 % – 9 %, and decrease of shear strength in 30 % – 35 %. Wood also changes in colour and becomes darker. For samples of bigger thickness lower drying temperatures are applied [5].

Drying duration depends on the drying regimes, assortment measures, initial and final moisture content, drying quality, *etc*.

Wood drying at ambient air conditions does not change any properties, while drying temperature above 40 °C cause chemical changes that influences wood properties changes. More intensive changes are achieved at high temperatures [8].

The destruction of main wood structural components such as hemicellulose, cellulose and lignin under temperature differ. Destruction of lignin and cellulose is slower and needs higher temperature than that for hemicellulose [9]. Destruction of extractive materials is easier due to evaporation during heating. The greatest structural changes are achieved at temperatures above 200 °C [10]. The essential physical and mechanical properties changes are observed above the 150 °C [10, 11]. In some cases destruction of wood components can be observed already at 100 °C [12].

Mechanical properties at the same heating conditions change in different modes. For example wood heating at 100 °C – 120 °C for 30 – 60 hours decreases static bending, tension and compression strength in 8 % – 9 %, while resistance to split and impact bending can decrease down to 15 % – 20 % [3].

Many wood properties are related to the wood density, which depends on the width of annual rings [2]. For example for spruce the smaller width of annual rings the bigger density of wood. The width of the rings is assumed as amount of rings in one centimetre. For each wood species optimal amount of rings is characteristic, after which physical and mechanical properties decreases. The

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highest density pinewood shows at ring width of 1.4 mm [13].

For high quality oak wood number of annual rings must be not bigger than 12, for ash that is up to 9 per cm. Percentage annual rings of late wood usually is accepted as main factor on which density of wood depends. That is due to the fact that structural elements of early wood consist of thin walls and wide cavities. That is why wood is more porous, while late wood shows significantly higher density [13].

Wood can be compressed perpendicular and parallel to the grain. Compression parallel to the grain is common in wood constructions, i. e. in the top and bottom of horizontal joining elements or vertical elements in which load is applied from the both sides [14, 15]. Resistance to the compression perpendicular to grain depends on the wood microstructure and loading direction (radial or tangential).

The aim of this investigation was to find relations between thermal treatment regimes and mechanical properties of the pinewood.

2. EXPERIMENTAL

The timber blanks were prepared from the untreated pinewood. They were dried in ambient air conditions for 3 months up to the moisture content of 9 % – 10 %. Cross-sections of the prepared samples was 20 mm × 20 mm, length of samples for compression and static bending tests was 30 mm and 300 mm respectively.

In order to eliminate influence of the rings, the curvature cross-section of samples was small. Annual rings were parallel to the one sample edge and lengthwise axis was parallel to the grain. Only samples without defects were selected for the tests. Conventional density of samples was 400 kg/m^3 – 422 kg/m^3.

For each test 16 groups of prepared samples and one reference untreated group was tested.

For static bending test one group consisted of 37 samples, for compression test parallel to the grain – 28 samples and perpendicular to it – 140 samples [12].

Test group was selected from the samples in which each third part was with wide (10 rings per centimetre), medium (from 10 to 15 rings per cm) and narrow (more than 15 rings per cm) annual rings.

The heating temperature and duration were selected close to the technological drying regimes. Drying temperature was 60, 80, 100 and 120 °C and drying duration was 24, 48, 72 and 96 hours.

After heating samples were left for several weeks at ambient air conditions to reach characteristic moisture content.

Mechanical tests were performed according to the standards ISO 3132-1975, ISO 3133-1975 and ISO 3787-1976 [16 – 18].

Compression was performed during testing samples parallel and perpendicular to the grain.

Wood compression strength parallel to the grain $f_{c,0}$ was calculated according to the formula :

$$f_{c,0} = \frac{F_{max}}{a \cdot b}, \text{ MPa}, \quad (1)$$

where F_{max} is maximal load, N; a and b are linear dimensions of sample cross section, mm.

Wood compression strength perpendicular to the grain was calculated as follows:

$$f_{c,90} = \frac{F_{c,90}}{b \cdot l}, \text{ MPa}, \quad (2)$$

where $F_{c,90}$ is the force corresponding to the limit of proportionality (in the case of three phase deformation) or maximal load (in the case of one phase deformation), N; b and l is respectively sample width and length, mm.

Scheme of static bending test is presented in Fig. 1.

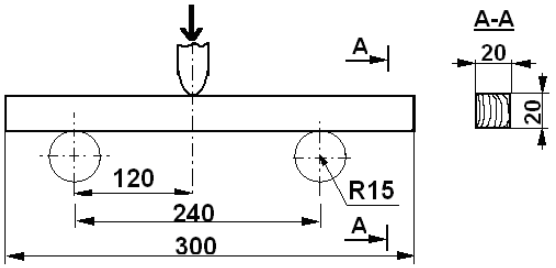

Fig. 1. Principal scheme of static bending test

Bending strength f_m was calculated according to the formula:

$$f_m = \frac{3 \cdot F_{max} \cdot l}{2 \cdot b \cdot h^2}, \text{ MPa}, \quad (3)$$

where F_{max} is maximal force during bending, N; l is distance between supports, mm; b is sample breadth, mm; h is sample height, mm.

Loading (both compression and bending) of the samples was performed with constant loading speed on universal testing machine that the test piece was broken in 1.5 min ±0.5 min from the beginning of the loading. Load was determined with the accuracy which does not exceed 1 %.

Experimental results has revealed following tolerance of statistical parameters: for bending test standard deviation was $S = (1.4 – 2.17)$ %, variation was $V = (7.9 – 11.0)$ %, precision index of an average value was $P = (2.1 – 3.8)$ %. For compression statistical parameters varied as follows: $S = (0{,}36 – 5{,}9)$ %, $V = (4{,}5 – 14{,}5)$ %, $P = (1{,}72 – 3{,}61)$ %.

3. RESULTS AND DISCUSSION

After experimental testing compression strength according Eq. 1 and Eq. 2 and bending strength according Eq. 3 was calculated. Statistical analysis of obtained results was performed using methodology presented in [19].

As the moisture content of investigated samples was not equal to 12 % (it varied from 9 % up to 19 %) compression and bending strength was recalculated using Eq. 4 to the normalized moisture content:

$$f_{12} = f\left[1 + \alpha(\omega - 12)\right], \quad (4)$$

where α is the correction coefficient of moisture content; ω is the sample moisture content, %.

The obtained results presented in Table 1 and Fig. 2 – 5.

During bending, in the top layers of wood samples compression stresses are found while in the bottom layers –

tension stresses dominates. This situation is more characteristic for concentrated loading mode.

As the compression strength of wood is significantly lower than that of tension, the initial micro cracks were observed in the compression zone while final fracture and macro cracks of samples usually in the tension zone occur.

As it can be seen from the results presented in Table 1 strength of thermally treated pinewood during static bending decreases compared to that of untreated. After heating at 60 °C temperature static bending strength decreases by 5.13 % – 9.0 % compare to those of untreated.

As the highest 9.4 % decrease was found for 48 hours thermally treated samples, that confirm suggestion [3] that wood heating at 60 °C does not results in the wood structural changes. For the samples heated at temperature of 80 °C for different durations (from 24 up to 96 hours) strength decreases by more than 5 % (5.88 % – 10.03 %). Bending strength decreases by 5.73 % – 12.52 % after heating at temperature of 100 °C, and at temperature of 120 °C that is from 11.46 % to 13.73 %.

Table 1. Wood strength in dependence on heating temperature and duration

Duration, h	Untreated	Temperature, °C			
		60	80	100	120
strength in static bending, MPa					
untreated	84.11	-	-	-	-
24	-	78.91	75.67	79.29	74.47
48	-	76.20	78.10	77.16	74.41
72	-	79.79	79.13	73.58	72.89
96	-	79.15	77.45	75.10	72.55
compression strength perpendicular to the grain (tangential direction), MPa					
untreated	7.67	–	–	–	–
24	–	7.47	7.49	7.53	7.52
48	–	7.02	7.62	7.51	7.26
72	–	7.51	7.28	7.67	7.86
96	–	7.52	7.17	7.86	7.73
compression strength perpendicular to the grain (radial direction), MPa					
untreated	3.74	–	–	–	–
24	–	3.83	3.26	3.5	3.4
48	–	3.66	3.36	3.44	3.36
72	–	3.57	3.32	3.92	3.65
96	–	3.61	3.57	3.42	3.64
compression strength parallel to the grain, MPa					
untreated	41.35	–	–	–	–
24	–	45.32	47.63	46.17	41.06
48	–	43.90	45.20	42.80	42.17
72	–	45.26	44.64	41.38	43.97
96	–	47.37	48.91	41.45	44.40

Independently on the treatment duration the increase of thermal treatment temperature results on the decrease of bending strength. After 24 hours of thermal treatment bending strength decreases by 5.37 % – 11.46 %, after 48 hours 7.15 % – 11.53 % and after 72 hours that is 5.13 % – 13.34 %. More significant changes were obtained for samples heated for 96 hours. The decrease of bending strength compare to untreated samples was found from 5.98 % down to 13.75 %.

From the data presented in the Table 1 it is evident that heating decreases compression resistance perpendicular to the grain. Compression in tangential direction for samples heated at temperature of 60 °C decreases by 2 % – 8.5 %, at temperature of 80 °C decrease is about 0.6 % – 6.5 %, at 100 °C that is 0 % – 2 % and at 120 °C compression strength decreases from 2 % down to 5.3 %.

The more significant strength decrease of compressed perpendicular to the grain in tangential direction samples was found for heated at temperature of 60 °C and 80 °C for 48 hours samples.

Compression strength perpendicular to grain in the radial direction after heating at 60 °C decreases about 2.2 % – 4.7 %, at 80 °C that is 4.6 % – 12.7°%, at 100 °C – 6.5 % – 8.0 % and at 120 °C decrease is from 2.5 % down to 10 %. It is clear that more significant compression strength changes are achieved at temperature of 80 °C.

As it can be seen from the Table 1 compression strength of pinewood samples loaded parallel to the grain after heating increases. After heating at 60 °C, 80 °C, 100 °C and 120 °C, strength increases respectively 6 % – 14.5 %, 8 % – 18.3 %, 0.1 % – 11.7 % and 2 % – 7.4 %. These results indicate that more significant changes are achieved during heating at temperature of 60 °C and 80 °C at heating duration for 96 hours. Obtained data coincide well with those obtained in literature [20, 21]. Also it can be found results, which indicate that after heating compression strength parallel to the grain can decrease [3, 12, 13]. The increase of compression strength parallel to the grain can be related to the structural wood changes. Heating initiates destruction of hemicellulose earlier than degradation of cellulose and lignin. The degradation of long hemicelluloses chains into shorter ones creates specific structure, which is resistant to the compression parallel to the grain [21].

The obtained results confirm suggestion that influence of heating temperature is more significant than heating duration [20]. Comparison of obtained results indicates that heating at lower temperatures but longer duration does not shows results equal to those obtained at higher temperature and shorter duration.

Average number of annual rings (or width of annual rings) also influences mechanical and physical properties of wood.

As it can be seen from the Fig. 2 static bending strength of pinewood samples is lowest when number of annual rings is low ($n < 10$). Static bending strength increases when number of annual rings per 2 cm increases.

Pinewood compression strength parallel to the grain is lowest when number of annual rings is lowest – they are wide (Fig. 3). When rings are narrow (its number in the sample is higher than 15) or middle (number of annual rings vary in the range from 10 up to 15), the dependence between number of annual rings and compression strength is not clear. The clear increase of compression strength

with increase of number of annual rings was found for 63 % of investigated samples.

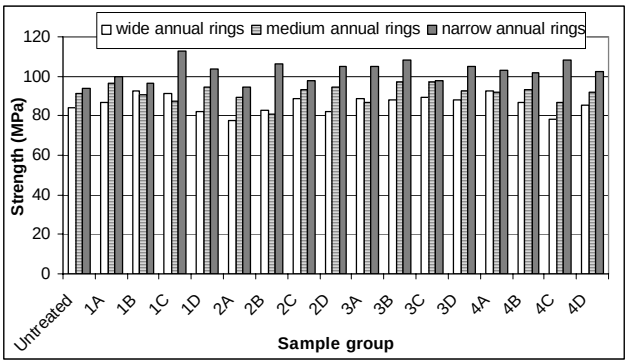

Fig. 2. Bending strength *vs* width of annual rings, heating duration (1, 2, 3, 4 is heating duration respectively 24, 48, 72 and 96 hours), and heating temperature (A, B, C, D is respectively 60, 80, 100 and 120 °C)

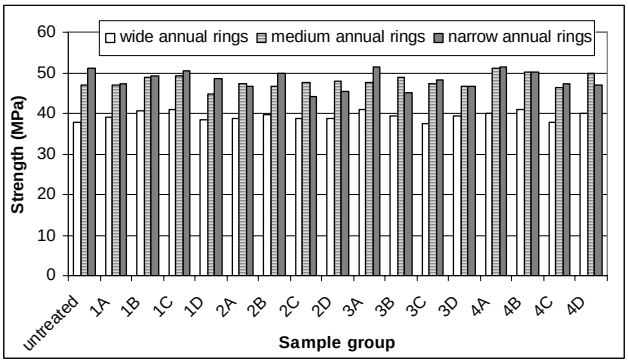

Fig. 3. Compression strength parallel to the grain *vs* width of annual rings, heating duration and temperature (marking as in Fig. 2)

The highest compression strength perpendicular to the grain in tangential direction was achieved for samples with medium number of annual rings (from 10 to 15 and width of rings equal to 1.3 mm – 2 mm) (Fig. 4). This fact confirms suggestion that highest strength of pinewood is achieved when width of annual rings is about 1.4 mm. 56 % of tested samples with lowest number of annual rings shows lowest compression strength perpendicular to the grain in tangential direction.

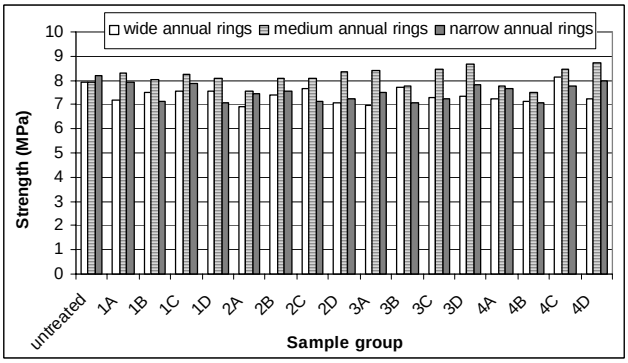

Fig. 4. Compression strength in the tangential direction *vs* width of annual rings, heating duration and temperature (marking as in Fig. 2)

During compression perpendicular to the grain in the radial direction opposite tendency occur: decrease of number of annual rings results on the decrease of compression strength (Fig. 5).

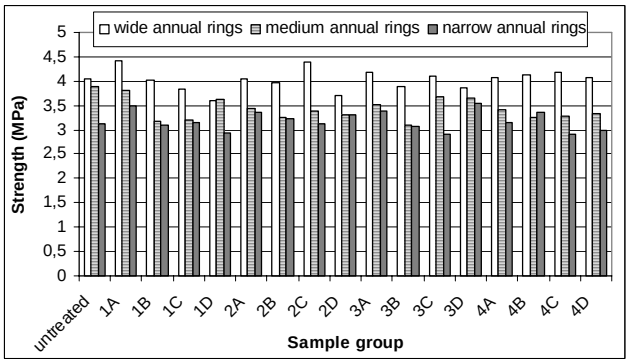

Fig. 5. Compression strength in the radial direction *vs* width of annual rings, heating duration and temperature (marking as in Fig. 2)

As it can be seen from the Figs. 2 – 5 the strength of pinewood is independent on the number of annual rings when both heating temperature and duration vary. The character of dependencies between static bending strength and width of annual rings does not changes under thermal treatment of the pinewood.

4. CONCLUSIONS

The influence of thermal treatment (temperature and duration) on the bending strength, compression resistance parallel and perpendicular to the grain has been investigated. It was shown significant influence of thermal treatment on the mechanical properties of pinewood.

As advantage of thermal treatment is the increase of the wood compression resistance parallel to the grain. While strength perpendicular to the grain decreases. Higher intensity of changes was found for compression resistance parallel to the grain, compare to decrease of strength perpendicular to the grain.

Independently on the thermal treatment regimes bending strength of pine wood decreases. The increase of thermal treatment duration and temperature increase intensity of observed changes.

Average width of annual rings or number of annual rings in the sample cross-section also influences properties of pinewood. Compression strength parallel to the grain reaches its lowest values when amount of annual rings is lowest, while in case of medium and narrow rings this effect for pinewood is not characteristic. Compression strength perpendicular to the grain in the tangential direction is highest when number of annual rings is medium, while in radial direction opposite effect was found: compression resistance increases when number of annual rings decreases. Static bending strength is lowest when number of annual rings is lowest. It was found that thermal treatment does not affect character of dependencies between annual rings and mechanical properties.

REFERENCES

1. APA Engineered Wood Handbook. Ed. by T. G Williamson. New York: McGRAW-HILL, INC., 2002: 895 p.
2. **Bowyer, J. L., Shmulsky, R., Haygreen, J. G.** Forest Products and Wood Science: an Introduction. Ames [Ia.]: Iowe State Press, 2003: 554 p.
3. **Kajalavičius, A., Albrektas, D.** Theory and Equipment of Wood Hydrothermal Treatment. Kaunas: Technologija, 2008: 168 p. (in Lithuanian).
4. **Korkut, S., Bektas, I.** The Effects of Heat Treatment on Physical Properties of Uludag Fir (Abies bornmuelleriana Mattf.) and Scots Pine (Pinus sylvestris L.) Wood *Forest Products Journal* 3 2008: pp. 95 – 99.
5. **Yildiz, S., Gezer, E. D., Yildiz, U. C.** Mechanical and Chemical Behavior of Spruce Wood Modified by Heat *Building and Environment* 41 2006: pp. 1762 – 1766.
6. **Stenudd, S.** Color Response in Silver Birch During Kiln-drying *Forest Products Journal* 6 2004: pp. 31 – 36.
7. **Thompson, D. W., Kozak, R. A., Evans, P. D.** Thermal Modification of Color in Red Alder Veneer. I. Effects of Temperature, Heating Time, and Wood Type *Wood and Fiber Science* 5 2007: pp. 653 – 661.
8. **Sundqvist, B.** Color Response of Scots Pine (*Pinus sylvestris*), Norway Spruce (*Picea abies*) and Birch (*Betula pubescens*) Subjected to Heat Treatment in Capillary Phase *Holz als Roh- und Werkstoff* 60 2002: pp. 106 – 114.
9. **Hill, C.** Wood Modification: Chemical, Thermal and Other Processes; Wiley Series in Renewable Resources, 2006: 200 p.
10. **Mburu, F., Dumarcay, S., Bocquet, J. F., Petrissans, M., Gerardin, P.** Effect of Chemical Modifications Caused by Heat Treatment on Mechanical Properties of *Grevillea robusta* Wood *Polymer Degradation and Stability* 93 2008: pp. 401 – 405.
11. **Esteves, B. M., Domingos, I. J., Pereira, H. M.** Pinewood Modification by Heat Treatment in Air *Bio Resources* 3 (1) 2008: pp. 142 – 154.
12. **Yilgor, N., Unsal, O., Kartal, S. N.** Physical, Mechanical and Chemical Properties of Steamed Beech Wood *Forest Products Jąournal* 11/12 2001: pp. 89 – 93.
13. **Jakimavičius, Č.** Wood Science. Kaunas: Technologija, 2008: 272 p. (in Lithuanian).
14. **McKenzie, W., Zhang, B.** Design of Structural Timber to Eurocode 5. Palgrave Macmillan, 2007: 508 p.
15. **Valentavičius, A., Valiūnas, B.** Wood Constructions. Vilnius: Enciklopedija, 2000: 224 p. (in Lithuanian).
16. International Standart ISO 3132-1975 (E). Wood – Testing in Compression Perpendicular to Grain.
17. International Standart ISO 3133-1975 (E). Wood – Determination of Ultimate Strength in Static Bending.
18. International Standart ISO 3787-1976 (E). Wood – Tests Methods – Determination of Ultimate Stress in Compression Parallel to Grain.
19. **Pižurin, A. A., Rozenblit, M. S.** Investigation of Wood Treatment Processes. Moscow: Lesnaja promyshlennost, 1984: 232 p. (in Russian).
20. **Kaps, T., Kask, O.** Thermally Treated Wood-material for Traditional and Innovative Approach *Proceedings of Baltic Polymer Symposium – 2003,* Jurmala, September 17 – 19, 2003, RTU, Riga, 2003: pp. 21 – 25.
21. ThermoWood 2003. ThermoWood®Handbook 08.04.2003. www.thermowood.fi

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