Influence of Thermal Modification on Nail Withdrawal Strength of Spruce Wood

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This paper deals with nail withdrawal strength of spruce (*Picea abies* L.) with a focus on its dependence on thermal modification. Nail withdrawal strength is a feature of wood that is very important in the construction of wooden buildings. There are many studies dealing with the nail withdrawal strength of natural wood; however, this feature is much less explored with respect to thermally modified wood. Spruce wood was thermally modified at three different temperatures (140, 180, and 240 °C), and the nail withdrawal strength was evaluated for three types of nails driven into three anatomical directions. Values of nail withdrawal strength of thermally modified wood were compared with values of control spruce wood. The effect of thermal modification was clear: with increasing temperature, gradually decreasing values of nail withdrawal strength were obtained. The highest values were found in the tangential direction, and the lowest occurred in the axial direction. Annularly threaded nails had the highest values of nail withdrawal strength, while helically threaded nails had the lowest results.

Keywords: Nail; Withdrawal strength; Spruce wood; Thermal modification; Temperature; Anatomical direction

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INTRODUCTION

In the industry, wood is popular for its properties such as color, gluability, weight, and insulating ability against heat and vibration. However, wood also possesses properties that reduce the durability of products, especially when used outdoors. These properties include a high degree of dependence on moisture content and associated dimensional changes, as well as lower resistance to biotic factors. One of the ways to eliminate these negative characteristics is through thermal modification.

Thermally modified wood, also known as ThermoWood®, is a material whose principle was coined in Finland. ThermoWood® products are manufactured with a special patented process of heat treatment of wood. Thermal treatment of coniferous wood has a lasting effect on the physical and mechanical properties of the material (Požgaj *et al.* 1993; Yildiz *et al.* 2006; Esteves and Pereira 2009). This process creates a completely new material with properties comparable to those of hard and highly resistant wood species. The result is wood with significantly increased durability and resistance to rot and wood-destroying fungi (Reinprecht and Vidholdová 2008). Resistance can be increased up to the level of resistance of red cedar or hardwoods. The product also has excellent dimensional stability. Reducing the moisture content of the material by more than 50% is attained by significantly lowering the moisture absorption and shrinkage of the material (Mayes and Oksanen 2003). In addition, there are also numerous wooddeteriorating effects, such as bulging, twisting, warping, and other deformations. During the manufacturing process, the wood is heated and obtains an attractive brown color. Color modification depends on the production process; the higher the temperature, the darker the color. Production of thermally modified wood is environmentally friendly because the material does not contain any chemicals or reagents. Any residues of thermally modified wood can be incinerated or disposed of as normal wood waste. Thermally modified wood can be used for many interior applications, such as windows, doors, flooring, interior construction, saunas, garages, as well as in the exterior for cladding, stairs, terraces, railings, fences, and noise barriers (Viitaniemi 2000).

Nails are among the most commonly used fasteners for wooden structures and have a very wide application (Wills *et al.* 1996). Nailed joints in some cases complement carpentry joints. Nailed joints have advantages such as easy creation, low price, and simple construction. For properly made joints, it is important to choose suitable nails, not only in terms of length, but also the thickness, *i.e.*, diameter. The essence of a nail joint is friction between the wood and the driven nail. This friction depends primarily on the depth of the nail's penetration in the wood and wood fiber structure around the shank. The strength of the nail joint is defined as the specific resistance of the wood to the extraction of nails (nail withdrawal strength or nail holding power). The nail withdrawal strength is a function of nail diameter, its driven length, and the grain direction and density of the wood into which it is driven. Nailed joints strength can be increased by changing the shape of the shank (*e.g.* square cross-section) or modification of shank using threads. While common nails have smooth shanks, threaded nails form shanks with threads. The most common modification of a nail shank is making helical or annular threads. Smooth nails provide joint strength by friction between the surface of the shank of the nail and the wood. Helically and annularly threaded nails create joint strength by friction and by wood fibers lodged between the threads. These wood fibers, lodged in the threads, must be broken to pull out a threaded nail from the wood (Rammer *et al.* 2001). Therefore, in general, threaded nails should have higher nail withdrawal strength, and when used, do not need to be as long as smooth nails (Fig. 1).

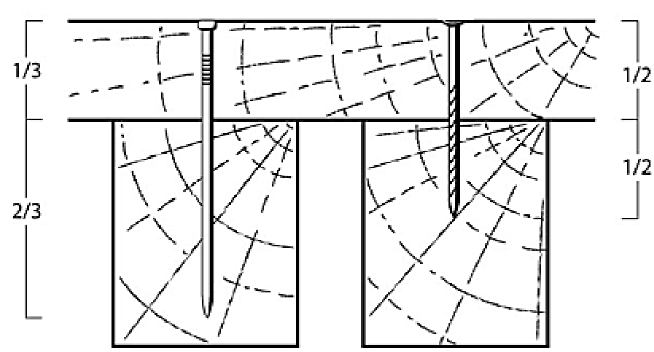

Fig. 1. Dependence of the length of nail on shank type

This research focused on the nail withdrawal strength of spruce because spruce wood is one of the most widely used and nails are the most basic type of fasteners. The main goal was examining the influence of the three types of nails, namely smooth, annularly, and helically threaded, on the nail withdrawal strength of control (unmodified) and thermally modified spruce wood. Thermal modification was carried out at three different temperatures 140, 180, and 240 °C.

EXPERIMENTAL

Materials

Eighty-year-old European spruce trees (*Picea abies* L.) harvested near Kostelec nad Černými lesy, east of Prague, were used for the experiments. Suitable zones were cut from the trunk at a height of 2 m from the stump. The zones were cut into boards with dimensions of 55 × 400 × 660 mm, and these were used for thermal modification.

For each of the four groups (control and thermally modified at every three temperatures), a special set of samples were prepared for density and moisture content measurement. The dimensions of these samples were in compliance with relevant standards - ISO 3130 and ISO 3131. These samples were cut off from the samples for nail withdrawal strength after testing.

Procedure

Thermal treatment

Thermal modification was carried out in collaboration with a company known as KATRES Ltd. (Jihlava, Czech Republic). Spruce samples were modified in thermal furnace (LAC, type S250/03; Czech Republic) (Fig. 2). Thermal modification consisted of three basic phases (Fig. 3). The first phase was characterized initially sharp increase of temperature up to 100 °C when drying occurs. Then, there was a gradual increase up to 130 °C. In the second phase, the temperature was increased from 130 °C up to the required final temperature 140, 180, or 220 °C. This final temperature was kept for a further 3 h. The last phase served for gradual cooling of wood, which was completed at 40 °C, after which the thermal chamber was opened. Then, samples were acclimatized 3 h in the surrounding environment (Horejš 2014). Table 1 lists times for all thermal treatment phases.

Fig. 2. Laboratory thermal furnace S250/03 filled with spruce boards

Table 1. Procedures for Thermal Modification

Required final temperature (°C)	Thermal modification			
	I. phase (hours)	II. phase (hours)	III. phase (hours)	Total time (hours)
140	30	6	10	46
180	30	8	11	49
220	30	13	10	53

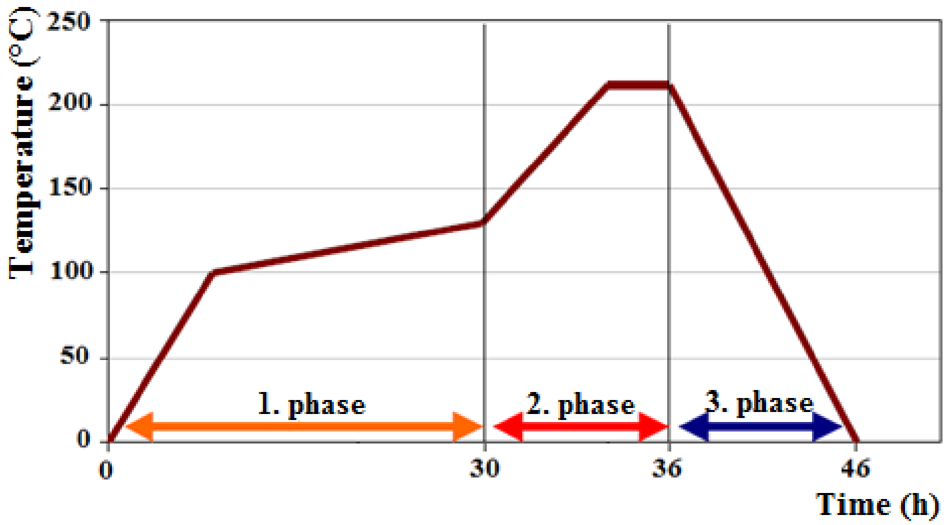

Fig. 3. Phases of thermal modification for final temperature 140 °C

All natural and thermally modified wood were cut to final dimensions of 50 × 50 × 150 mm for nail withdrawal strength testing, according to ISO 9087 (1998). Clear control and thermally modified samples were conditioned in a conditioning room (moisture content (ϕ) = 65 ± 3% and temperature (t) = 20 ± 2 ºC) for more than four months to achieve equilibrium moisture content (EMC).

Twenty samples were used for each combination of nail type and final temperature of modification, so the whole investigation contained 240 samples.

Withdrawal strength determination

Before testing, all samples were marked according to ISO 9087 (1998) (Fig. 5). Three types of steel flathead nails were selected for testing: smooth, helically threaded (spiral), and annularly threaded (ring shank) nails with dimensions of 2.8 x 50 mm (Fig. 4).

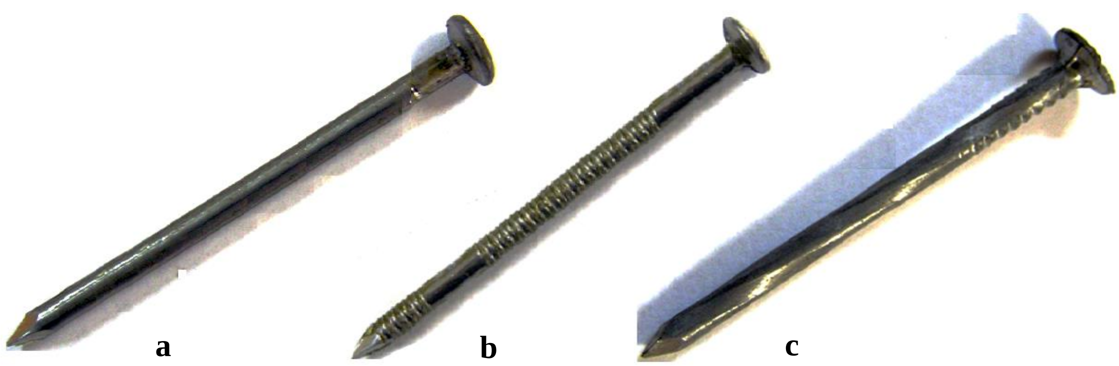

Fig. 4. Nail types for testing: (a) smooth, (b) annularly threaded, and (c) helically threaded

Two nails were driven into each surface (side) of the sample (radial, tangential, or axial cut), perpendicular to the surface. The depth of penetration of the nails was (without sharpening the tip) 30 ± 1 mm. Driven nails were pulled out the earliest after two hours and no later than three hours after driving. Then, samples were placed in the extraction jig (Fig. 6a) in a universal tensile machine UTS 50 (Testsysteme, Germany) with the TIRA system (Fig. 6b) and tested. Extraction of the nails was carried out with a continuous movement of the head of the testing machine at a constant rate. The rate of movement was such that the time taken for extraction was between 1 and 2 min.

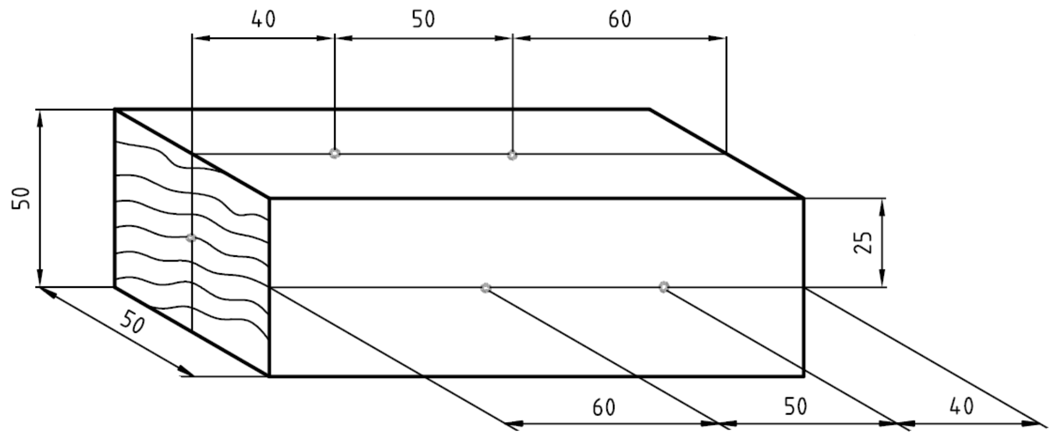

Fig. 5. Marking of test samples for insertion of nails

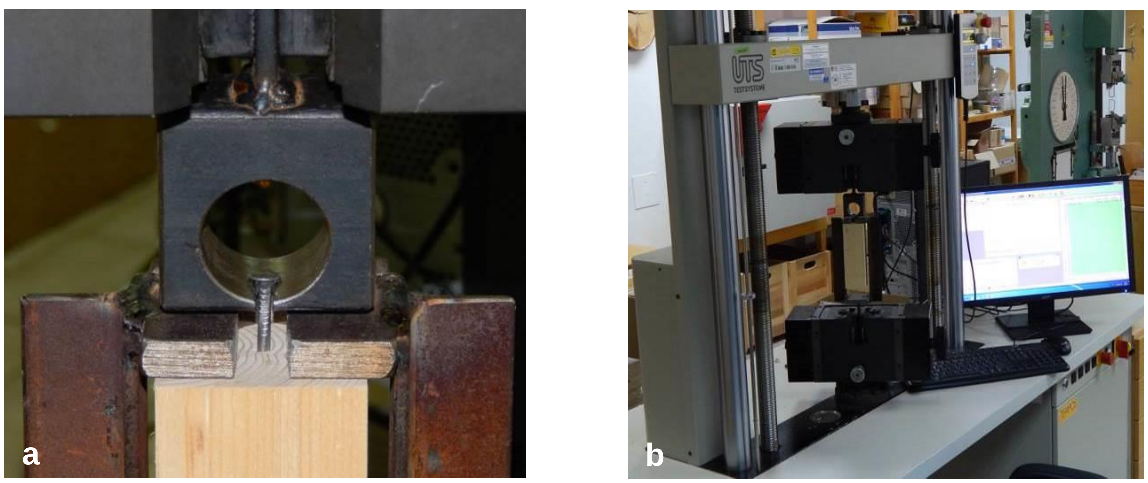

Fig. 6. (a) Placement of the sample in extraction jig and (b) universal tensile machine UTS 50 with TIRA system

Evaluation and Calculation

The influence of factors on the nail withdrawal strength was statistically evaluated using ANOVA analysis, mainly by Fisher's F-test, in STATISTICA 12 software (Statsoft Inc.; USA).

Nail withdrawal strength (also called holding power, withdrawal capacity, or withdrawal resistance) is a primary factor that varies due to thermal treatment. Nail withdrawal strength was calculated according to Eq. 1 from ISO 9087 (1998) and ČSN 49 0135 (1984),

$$\sigma_w = \frac{F_{max}}{l} \tag{1}$$

where σ_w is the specific resistance of the wood to the extraction of nails at a certain moisture content; w (N/mm), F_{max} is the maximum axial load force (N); and l is the depth of penetration of a nail (mm). Each final value of specific resistance of the wood to the extraction of nails is the arithmetic mean of the results of two measurements on each surface of each test piece according to ISO 9087 (1998).

The density was determined as an auxiliary indicator. Density was calculated according to Eq. 2 from ISO 3131 (1975),

$$\rho_w = \frac{m_w}{a_w * b_w * l_w} = \frac{m_w}{V_w} \tag{2}$$

where ρ_w is the density of the test sample at moisture content w (kg/m^3); m_w is the mass (weight) of the test sample at moisture content w (kg); a_w, b_w, and l_w are dimensions of the test sample at moisture content w (m); and V_w is the volume of the test sample at moisture content w (m^3).

The density of wood after treatment was calculated according to Eq. 3 from ISO 3131 (1975),

$$\rho_{tw} = \frac{m_{tw}}{a_{tw} * b_{tw} * l_{tw}} = \frac{m_{tw}}{V_{tw}} \tag{3}$$

where ρ_{tw} is the density of the test sample after treatment (kg/m^3); m_{tw} is the mass (weight) of the test sample after treatment (kg); a_{tw}, b_{tw}, and l_{tw} are dimensions of the test sample after treatment (m]; and V_{tw} is the volume of the test sample after treatment (m^3).

The moisture content of samples was determined and verified before and after thermal treatment. These calculations were carried out according to ISO 3130 (1975) and Eq. 4,

$$w = \frac{m_w - m_0}{m_0} * 100 \tag{4}$$

where w is the moisture content of the samples (%); m_w is the mass (weight) of the test sample at moisture content w (kg); and m_0 is the mass (weight) of the oven-dry test sample (kg).

Drying to oven-dry state was also carried out according to ISO 3130 (1975), using the following procedure: wood samples were placed in the drying oven at a temperature of 103 ± 2 ºC until a constant mass was reached. Constant mass is considered to be reached if the loss between two successive measurements carried out at an interval of 6 h is equal to or less than 0.5% of the mass of the test sample. After cooling the test samples to approximately room temperature in a desiccator, the samples were weighed rapidly enough to avoid an increase in moisture content by more than 0.1%. The accuracy of weighing was at least 0.5% of the mass of the test sample.

RESULTS AND DISCUSSION

Physical Properties

The average equilibrium moisture content (EMC) of control and thermally modified spruce wood is listed in Table 2. The EMC values of native wood correspond to moisture content under conditions of φ = 65 ± 3% and t = 20 ± 2 °C. While the control spruce wood reached a moisture content of approximately 12%, thermal modification reduced EMC to half that of the unmodified wood (4 to 6%, depending on the temperature, as stated by Mayes and Oksanen 2003). Kariz *et al.* (2013) found 5% moisture content of spruce wood after thermal treatment at 230 °C, and Arnold (2010) found a 60% decrease in EMC after thermal modification at 180 to 220 °C. According to Vernois (2001), thermal modification at approximately 200 °C confers a lower hygroscopicity than the untreated wood and stabilizes the EMC at a value of 4 to 5%, while the unmodified wood has a value of 10 to 12%.

Table 2. Final Temperature, EMC, and Average Density of Tested Spruce Wood

Samples	**Required Final Temperature** (°C)	**Equilibrium Moisture Content** (%)	**Average Density** (kg/m^3)
I. Control	-	11.8	433 (9.18)
II. Group	140	5.1	421 (3.78)
III. Group	180	4.2	418 (6.57)
IV. Group	220	3.4	408 (4.91)

Each mean density (±SD) represents 20 wood samples

The average density of control spruce was 433 kg/m^3. This value corresponds to the 420 kg/m^3 indicated by Mayes and Oksanen (2003) or 443 kg/m^3 found by Kariz *et al.* (2013). Arnold (2010) found a lower value of density, 402 kg/m^3.

On the other hand, the density of thermally modified spruce wood was lower by 25 kg/m^3, which represents an approximately 6% density reduction at 220 °C. Arnold (2010) found a 5% decrease in density caused by thermal treatment. Mayes and Oksanen (2003) stated that the density of thermally modified wood ranged between 4.4 to 5.5%. However, Yildiz (2002) reported that thermal treatment of spruce at 220 °C decreased density by about 10.53%.

Nail Withdrawal Strength

The statistical results revealed that the influence of all monitored factors on the nail withdrawal strength was statistically significant (Table 3).

Table 3. Influence of Individual Factors and their Interactions on Nail Withdrawal Strength

Monitored factor	**Sum of Squares**	**Degree of Freedom**	**Variance**	**Fisher's F - Test**	**Significance Level P**
Intercept	142,778.5	1	142,778.5	23,704.76	0.000
Temperature	1270.7	3	423.6	70.32	0.000
Nail type	20,942.2	2	10,471.1	1,738.46	0.000
Anatomical direction	9,685.0	2	4,842.5	803.98	0.000
Temperature * nail type * anat. direction	174.2	12	14.5	2.41	0.004
Error	4,119.9	684	6.0		

Figure 7 clearly shows that increasing the temperature of the modification reduced the nail withdrawal strength, *i.e.*, the lowest values were found at 220 °C. The same temperature effect on withdrawal strength was also confirmed by Kariz *et al.* (2013) and Poncsák *et al.* (2006). Differences in the values of nail withdrawal strength, between control and thermally modified wood at 220 °C, were about 20%. The higher temperatures weaken the bonds between the components of wood, thereby reducing their coherence, and thus the overall strength of the wood. This effect was the strongest above the temperature of 200 °C. Madhoushi *et al.* (2010) examined the effect of densification and steaming temperature on nail withdrawal strength in eastern cottonwood. They found that the effect of steaming temperature (120, 140, and 160 °C) was not significant.

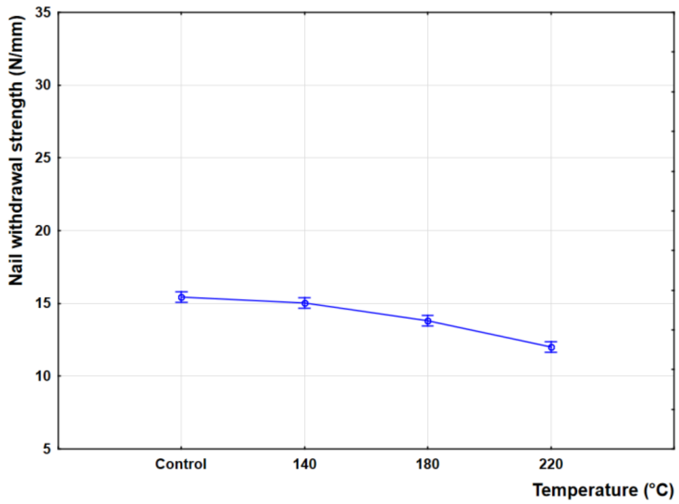

Fig. 7. The influence of temperature on nail withdrawal strength at the 95% confidence interval

The highest values of nail withdrawal strength were clearly achieved with annularly thread nails (Fig. 8). These values were about 40% higher than the values for smooth nails. They were more than twice as high as those achieved from the helically threaded nails (when considering only nail type). The fact that annularly threaded nails reached the highest value of nail withdrawal strength is also confirmed by other authors (Rammer *et al.* 2001; Celebi and Kilic 2007). These authors also stated that helically threaded nails have significantly higher values compared to smooth nails.

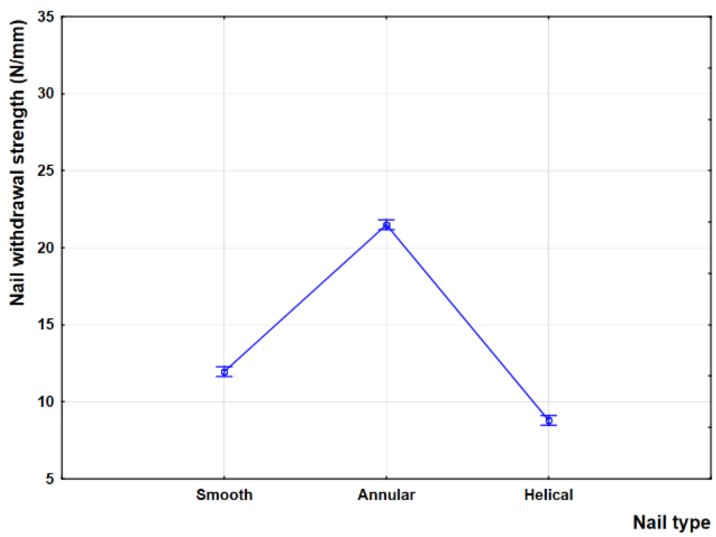

Fig. 8. The influence of nail type on nail withdrawal strength at the 95% confidence interval

However, the present did not confirm this fact. Rather, an opposing trend was observed. Lower values of nail withdrawal strength were achieved because of threads, which had only a slight angle. This slight angle did not ensure adequate friction and thereby decreased strength of the wood and nails.

Another factor is the influence of anatomical direction in which nails were hammered (Fig. 9). On the basis of the results, it is evident that the highest values were achieved in the tangential direction, while the lowest occurred in the axial direction. While the differences between our values obtained in the tangential and radial directions were not great, Akyildiz (2014) and Aytekin (2008) reported the highest values for nail withdrawal strength for the radial direction. In general, the lowest values of nail withdrawal strength are achieved always in the axial direction, which is caused by the wood structure and the orientation of the wood elements. The fact that the nail withdrawal strength is lowest in the axial direction was also confirmed by Aytekin (2008).

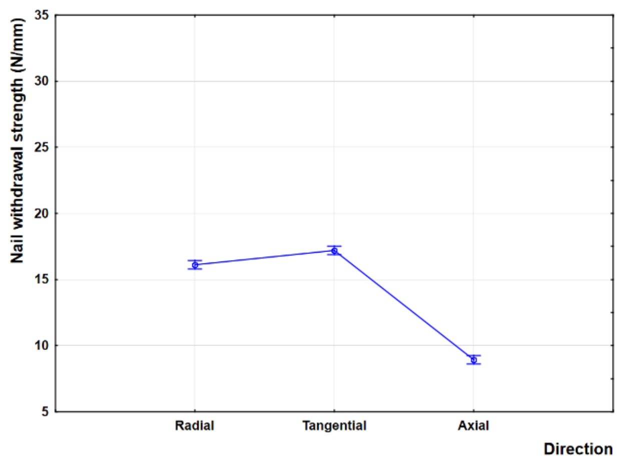

Fig. 9. The influence of anatomical direction on nail withdrawal strength at the 95% confidence interval

Figure 10 shows the effect of all factors simultaneously. Comparing the values of nail withdrawal strength, it can be clearly seen that the annularly threaded nails are significantly different than the smooth or helical nails in the radial and tangential direction, especially in control samples, while an increasing temperature of modification reduced these differences. Smooth nails have different values at higher temperatures of modification; there was a sharp decline in values with an increase in temperature. The sharpest decline occurred in the radial direction, which was even lower than in the axial direction (Table 4). All these facts can be explained by the higher rate of degradation of wood at temperatures above 200 °C, which has been confirmed by many authors. Poncsák *et al.* (2006) found that thermal modification changes the structure of the wood, which becomes less strong and more brittle. Phuong *et al.* (2007) found that the loss of strength and brittleness of wood formation is mostly due to the degradation of amorphous polysaccharides.

Nail withdrawal strength reduction is partially caused by a reduction in the density of wood, which generally leads to the deterioration of all mechanical properties (Mayes and Oksanen 2003). This nail withdrawal strength dependence on the density was confirmed by Madhoushi *et al.* (2010), who found that when the density was increased due to densification, there was also an increase in nail withdrawal strength. Also

Taghiyari *et al*. (2012) confirmed that the nail withdrawal strength is closely associated with the density.

Moisture content also has some influence on strength properties of wood. In general, decrease of moisture content improves the mechanical properties of wood (Bomba *et al*. 2014; Gaff 2014). This reduction of moisture content is a side-effect of thermal modifications. On the other hand, thermal modification changes the structure of wood considerably and therefore the positive effect of the decrease of moisture content is negligible. This change in structure due to high temperatures is one of the main causes of the loss of strength of wood and increasing its fragility.

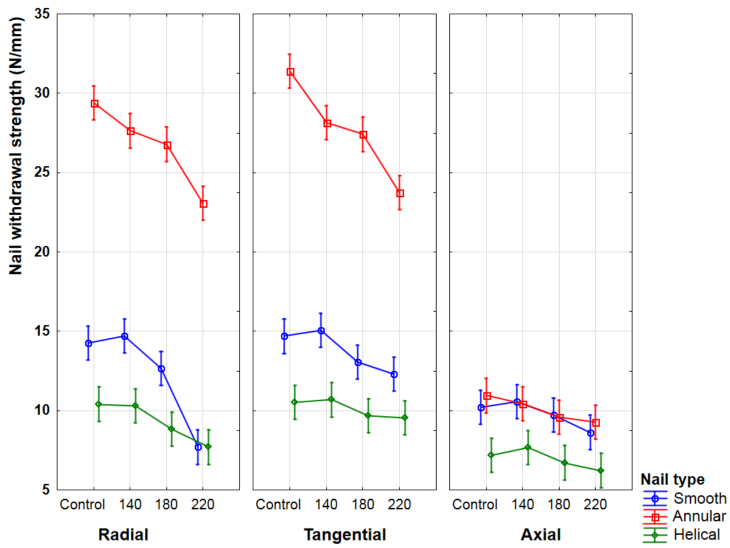

Fig. 10. The influence of temperature, nail type, and anatomical direction on nail withdrawal strength at the 95% confidence interval

Table 4. Average Values of Nail Withdrawal Strength

Nail Type	Anatomical directions	Nail Withdrawal Strength (N/mm)			
		Control wood	Thermally modified wood		
			140 °C	180 °C	220 °C
Smooth	Radial	14.27 (7.86)	14.72 (4.31)	12.67 (6.90)	7.70 (5.72)
	Tangential	14.70 (7.05)	15.06 (1.36)	13.07 (2.27)	12.31 (10.11)
	Axial	10.22 (2.94)	10.43 (3.40)	9.58 (2.64)	8.63 (8.14)
Annularly Threaded	Radial	29.39 (3.29)	27.64 (6.64)	26.79 (8.67)	23.07 (11.71)
	Tangential	31.39 (9.83)	28.15 (6.20)	27.42 (12.08)	23.74 (3.65)
	Axial	10.95 (5.56)	10.58 (2.69)	9.72 (9.87)	9.28 (2.11)
Helically Threaded	Radial	10.41 (3.61)	10.29 (4.15)	8.84 (11.09)	7.70 (7.24)
	Tangential	10.52 (8.14)	10.69 (1.39)	9.69 (3.30)	9.55 (8.43)
	Axial	7.18 (5.74)	7.69 (4.57)	6.71 (7.45)	6.23 (10.24)

Each mean nail withdrawal strength (±SD) represents 20 wood samples

At temperature 140 °C, smooth nails did not achieve lower values of nail withdrawal strength in all three directions. Conversely, there was a slight increase compared to the control wood. This increase can be explained by the fact that there was a loss of moisture content (Table 2), but the structure of wood was not breached. Wood moisture content dropped by more than half (Mayes and Oksanen 2003), and this led to a slight improvement in mechanical properties.

When using nails to join thermally modified spruce wood, annularly threaded nails instead of smooth nails should be chosen. Annularly threaded nails have the highest nail withdrawal strength and therefore can be shorter than the smooth nails. Helically threaded nails can also be used, but they should have a greater angle of threads (more threads *per* shank length), plus a longer shank or larger diameter, to ensure sufficient strength.

CONCLUSIONS

1. In our research, the highest values of nail withdrawal strength were found with the control (unmodified) spruce wood. The nail withdrawal strength gradually decreased with increasing treatment temperature.
2. Annularly threaded nails achieved the highest nail withdrawal strength. The lowest values were found for helically threaded nails, which had even slightly lower values than smooth nails.
3. Nails inserted in the tangential direction had the highest withdrawal strength values, while the lowest withdrawal strength values were in the axial direction.

ACKNOWLEDGMENTS

The authors are grateful for the support of Grant Agency of Faculty of Forestry and Wood Science, project No. 20123144, “Evaluation of the properties of materials used in wooden structures”. The authors wish to thank the company KATRES Ltd., Jihlava, Czech Republic for their co-operation and as well as the possibility of providing their equipment to create of thermowood for research.

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Article submitted: June 18, 2014; Peer review completed: August 6, 2014; Revised version received and accepted; August 11, 2014; Published: August 15, 2014.