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RADIAL VARIATION OF MECHANICAL PROPERTIES OF SPRUCE WOOD (*PICEA ABIES* L.) IN TENSION ALONG THE GRAIN

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SYNOPSIS. The paper reports results of a study on variation in density, strength and modulus of elasticity in early and latewood of spruce (*Picea abies* L.) measured in microtome samples along the grains upon tensile stress application as a function of cambial age. The measurements permitted to calculate the specific values of tensile strength and modulus of elasticity. Analysis of these specific parameters provided information on the effect of changes in the wood cell walls determined by MFA on the mechanical properties of wood.

KEY WORDS: spruce wood, tensile strength, modulus of elasticity, specific strength, specific modulus of elasticity, MFA

INTRODUCTION

Within a given tree species, the main factor determining the radial variation of physico-mechanical wood properties is the cambial age of annual rings. Juvenile wood of coniferous species has much poorer mechanical properties than mature wood, mainly because of looser packing of cell walls in a unit volume (lower density) and poorer quality of the cell walls manifested by smaller contributions of cellulose and greater microfibril angles. Another parameter influencing the quality of cell walls is the cell position in the annual ring. In general in earlywood the microfibril angles measured with respect to the longitudinal cell axes are greater than in latewood (Donaldson 1998, Herman et al. 1999, Barnett and Bonham 2004, Anagnost et al. 2005, Jordan et al. 2005, Fabisiak and Moliński 2008). As in S2 layer of the secondary cell wall of late tracheids MFA are steeper than in earlywood tracheids, the diversification of the mechanical properties of wood along the grain within individual annual rings is greater than expected on the basis of differences in density. Within individual annual rings the variation of mechanical properties is thus a resultant of the cell walls packing in a unit volume and their technological quality determined by MFA. In view of the above, it is obvious that the main factors influencing the technological quality of coniferous wood are the ultrastructure of cell walls and the contribution of latewood in annual rings (Via et al. 2009, Lachenbruch et al. 2010). In the period of earlywood growth, especially in the conditions favourable for earlywood development, the annual rings are wider and have lower contribution of mature wood and thus the wood has smaller density than the wood of narrow rings (Panshin et al. 1964, Zhang 1997, 1998, Alteyrac et al. 2006, Koizumi et al. 2005, Moliński and Krauss 2008).

Literature of the field brings many reports indicating that wood density is the most important parameter determining its properties (Bunn 1981, Bamber and Burley 1983, Dinwoodie 2000). This opinion follows from the fact that the relationship between wood density and its mechanical properties is directly proportional and characterised by relatively high correlation coefficient and the wood density is easily measurable. Thus, wood density has been commonly used for prediction of the technological quality of wood. However, according to many authors, the increase in the wood strength is much greater than expected on the basis of wood density growth only (e.g. Raczkowski 1965, Bunn 1981, Bamber and Barley 1983, Moliński and Raczkowski 1993, Zhang 1997). Similar observations have been made also to the wood modulus of elasticity (Cowdrey and Preston 1966 (after Cave and Walker 1994), Cave 1968, Bendtsen and Senft 1986, Yamashita et al. 2000, Donaldson 2008, Moliński and Krauss 2008). According to Bendtsen and Senft (1986) or Cave and Walker (1994) in the longitudinal direction MFA in S2 layer of cell walls have greater than density influence on the mechanical properties of wood. This observation has been fully confirmed in subsequent studies and is presently commonly accepted (Cave 1976, Dinwoodie 2000, Reiterer et al. 1999, Groom et al. 2002, Moliński and Krauss 2008, Krauss 2010). Important evidence supporting this opinion has been provided by Reiterer et al. (1999) for spruce wood (*Picea abies* L.). These authors proved that the strength of cell walls of early and late tracheids and their moduli of elasticity determined in microtome samples along the grains in tensile tests are the same on condition that MFA in these cells are the same.

This paper presents results of measurements of density, tensile strength and modulus of elasticity of spruce wood (*Picea abies* L.) as a function of cambial age of annual rings, determined in tension along the grain in microtome samples. These experimental data were used to calculate the specific values of tensile strength and modulus of elasticity. Analysis of variation in the latter brings the information on the effect of changes in the cell wall quality determined mainly by MFA on the mechanical properties of wood studied.

MATERIALS AND METHODS

The radial variation of mechanical properties of spruce wood was measured in microtome samples of radial direction width of about 200 µm, tangential width of 9 mm and length of 90 mm. The samples were sliced off from the earlier chosen annual rings from the board donated by the Department of Wood Science of Technical University in Zvolen (Slovakia), from a 65 year old spruce tree. Prior to slicing, the properly cut out board fragments were boiled for 24 h in distilled water. From each annual ring, depending on its width, from a few to up to twenty samples were obtained. The samples were conditioned in laboratory (T = 21°C, RH = 33-41%) till getting equilibrium moisture content. After stabilisation of the sample masses, their width was measured on an electronic growth ring measuring device BIOTRONIK with the accuracy of 0.01 mm, and their thickness by a micrometer screw with the accuracy of 0.001 mm at the centre of their length and at about 2 cm off the centre. The length of the samples was measured by a rule. Each sample was weighted on a laboratory balance with the accuracy of 0.001 g and the density of each sample was calculated. Prior to tensile test, the ends of the samples were protected against crushing by gluing to them hardboard pieces of 3 mm thick and 2 cm width, at the length of 2 cm.

Tensile test was carried out on a ZWICK ZO50TH machine with a BTC-EX-MARCO.001 extensometer. After introduction of the sample width and thickness to the machine, the tensile test was performed increasing the loading rate of 0.5 mm/min. The results approved for further analysis were those for the samples breaking more or less in the middle length.

In order to visualise the microfibrils in the tracheid walls from the same plank from which the test samples were obtained, a strip of wood of about 1 cm in thick-

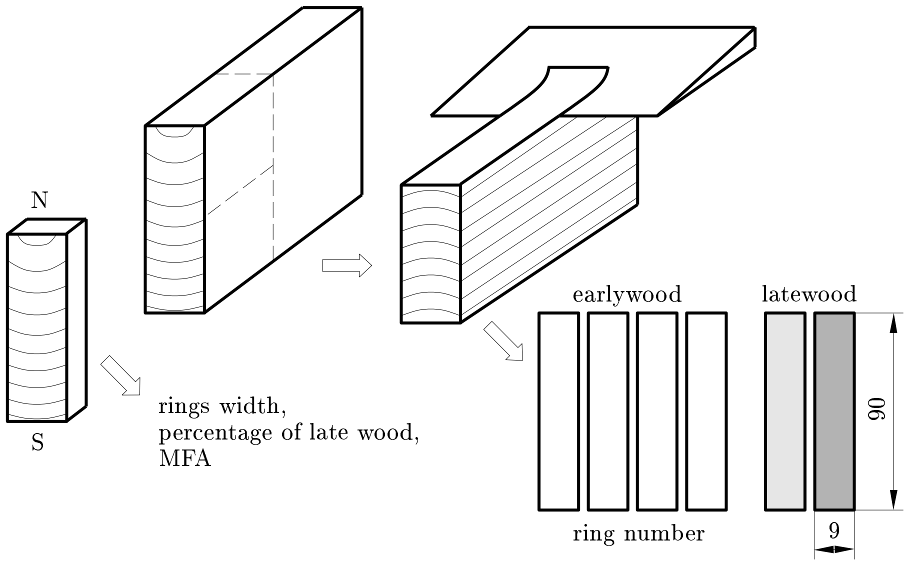

Fig. 1. Schematic procedure of sample preparation

ness was cut, divided into 3 parts and heated at 80°C for 24 h in a 20-% solution of $Cu(NO_3)_2$. From the same annual rings from which the samples for tensile test were made, also tangent microscope preparations were obtained of about 20 µm in thickness. In these preparations the MFA values were measured in tangent walls of the tracheids with the help of computer image analyser. In each annual ring the samples were sliced off at a distance of about 0.2 mm. After slicing the sample its position in the annual ring was identified by a Brinell magnifying glass. In each microscopic preparation 20 MFA were measured. The procedure of sample preparation is schematically shown in Figure 1.

RESULTS AND DISCUSSION

Results of the measurements expressed as the mean values for the samples from early and latewood separately and for individual annual ring are given in Table 1. The same table also gives the range of changes in MFA in the tangent walls of tracheids in particular zones of annual rings. To facilitate further analysis, the results of the tension test are also presented as a function of cambial age of annual rings in Figure 2, together with an analogous dependence of wood density. As follows from the plots, the density of earlywood shows a clear tendency to decrease with increasing cambial age of annual rings. Its lowest value of 270 kg/m^3 was noted in the ring 60, while its highest value of 360 kg/m^3 in the ring 20. The changes in latewood density showed the reversed tendency, it increased with increasing cambial age of annual rings from 645 kg/m^3 in the ring 5 to about 750 kg/m^3 in the ring 30 and for older rings it remained constant till the circumference. Interpreting the above differences in densities as indicators of cyclic inhomogeneity of wood (Raczkowski 1965), it can be concluded that juvenile wood is less inhomogeneous than mature wood. Similar observations concerning the radial variation in density of individual zones of annual rings have been made for other species of wood, e.g. *Tsuga heterophylla* (Panshin et al. 1964), *Picea mariana* (Zhang 1998), *Larix kaempferi* (Koizumi et al. 2005) and *Pinus sylvestris* (Moliński and Krauss 2008). The evidence collected proves that the radial increase in the bulk wood density of the above species is determined first of all by the latewood density changes.

As follows from the data presented in Figure 2, the wood density is not a reliable indicator of its tensile strength. The mechanical strength of earlywood as a function of cambial age of annual rings increases from 34 MPa in the ring 5 to 60 MPa in the ring 60 at clearly noted decrease in its density, whereas for the same rings the mechanical strength of latewood significantly increases from about 100 MPa to over 250 MPa (2.5 times) accompanied by very small increase in its density from 645 to 750 kg/m^3, so by 16%. Similar conclusions can be drawn for the wood modulus of elasticity. For earlywood it increases from 4.65 GPa in the ring 5 to 6.6 GPa in the ring 30, see Figure 3, and in older rings it slightly decreases reaching 6.1 GPa in the ring 62. For latewood the modulus of elasticity continuously increases with the cambial age of annual rings, from 15.3 GPa in the ring 5 to almost 27 GPa in

Table 1. Fundamental properties of the experimental material; mean values for wood of moisture content of about 5%

Earlywood

Cambial age of annual rings A [years]	Sample size n	Density ρ [kg/m^3]	Tensile strength TS [MPa]	Modulus of elasticity E [MPa]	MFA [°]		
					$X_{\min}$	X	$X_{\max}$
5	7	318	34	4 650	3.9	9.2	15.4
11	9	317	46	5 650			
15	10	330	58	5 600			
20	2	362	65	6 400	4.0	7.4	15.1
21	5	300	48	5 850			
26	7	301	46	5 650			
27	9	311	53	5 950			
30	4	325	64	6 600	2.2	5.1	7.3
32	3	325	49	6 800			
37	1	285	52	5 900	2.0	4.3	8.0
44	4	297	60	5 750	2.0	6.2	10.5
49	3	286	60	5 950	2.0	4.5	9.3
57	4	280	50	6 000			
60	2	268	49	5 250	1.9	4.4	9.0
62	2	303	60	6 100			

Latewood

Cambial age of annual rings A [years]	Sample size n	Density ρ [kg/m^3]	Tensile strength TS [MPa]	Modulus of elasticity E [MPa]	MFA [°]		
					$X_{\min}$	X	$X_{\max}$
5	4	645	106	15 300	5.3	7.9	10.2
11	2	750	110	19 200			
15	3	705	152	18 550			
20	2	715	163	16 600	3.9	5.9	8.4
21	3	719	166	21 550			
26	2	757	173	20 700			
27	3	729	180	19 350			
30	2	716	179	18 850	1.5	3.5	6.8
32	2	816	204	22 350			
37	2	760	230	24 700	0.5	2.9	6.7
44	2	754	222	25 300	1.4	3.4	7.0
49					1.0	3.1	5.1
57	2	747	262	23 800			
60	1	743	244	26 700			
62							

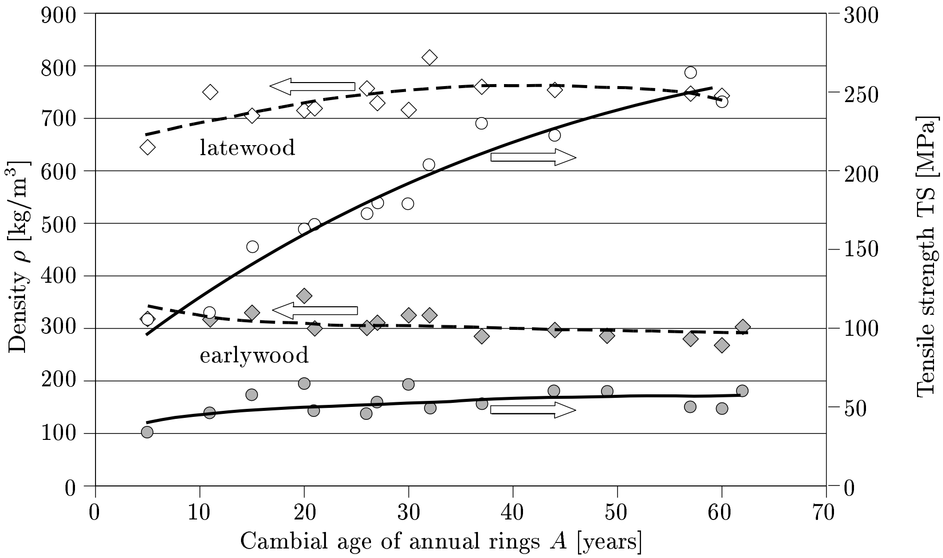

Fig. 2. Radial variation in early and latewood density and tensile strength versus cambial age of annual rings

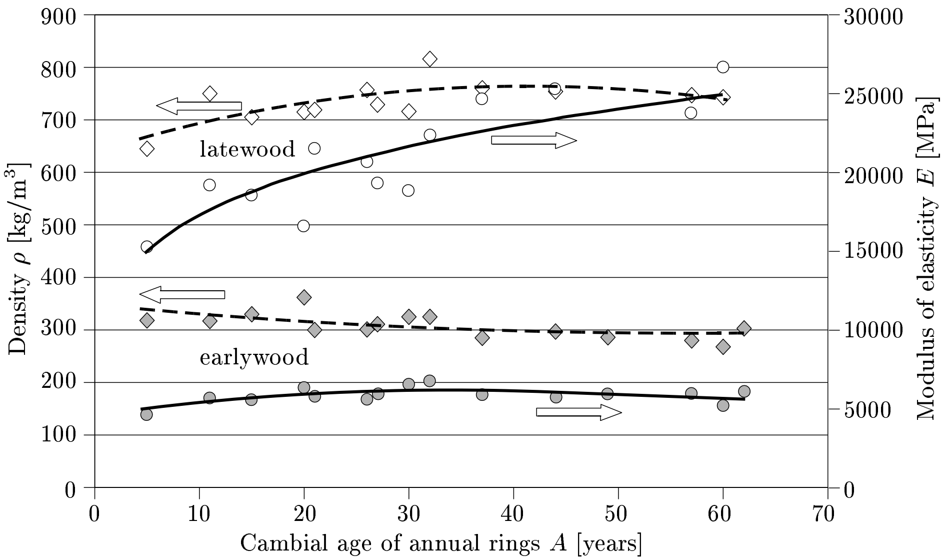

Fig. 3. Radial variation in early and latewood density and modulus of elasticity (measured in tensile test along the grain) versus cambial age of annual rings

the ring 60. The relation between the modulus of elasticity and wood density is shown in Figure 4. The density of the wood samples studied changed from about 300 kg/m^3 for earlywood to about 800 kg/m^3 for latewood. The difference in early and latewood density was 2.7 times, while the corresponding values of the modulus of elasticity were 5 and 25 GPa, so the difference was twice as great as the difference in density. The observed much greater increase in the wood mechanical properties than in its density confirmed the earlier reports to the same effect (Cave 1976, Bendtsen and Senft 1986, Dinwoodie 2000, Cave and Walker 1994, Reiterer et al. 1999, Groom et al. 2002, Moliński and Krauss 2008, Krauss 2010).

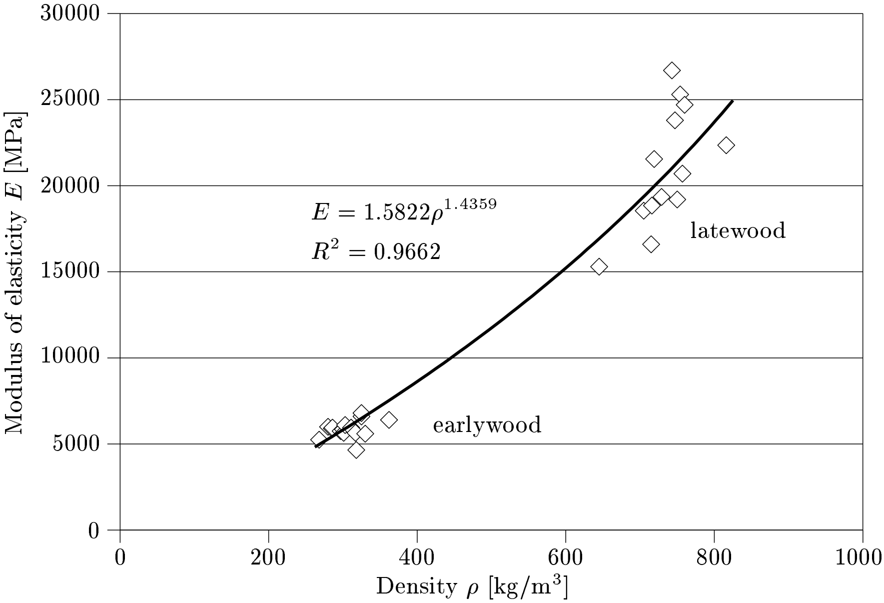

Fig. 4. The wood modulus of elasticity versus its density

The above relations can be explained taking into regard the changes in the angle of microfibrils to the longitudinal axis of the cell (MFA). It is well illustrated in Figures 5 and 6 presenting the specific tensile strength, specific modulus of elasticity and mean MFA values as functions of cambial age of annual rings. The specific values of tensile strength and modulus of elasticity are calculated as the ratios of the tensile strength and modulus of elasticity expressed in the unit of pressure to the wood density. Expressed in this form they illustrate the influence of factors other than density on the discussed mechanical properties of wood. The radial changes in specific tensile strength and modulus of elasticity are practically the mirror reflections of the MFA changes in the walls of tracheids in early and latewood. A decrease in MFA with increasing cambial age of annual rings is accompanied by increase in the tensile strength and modulus of elasticity. For earlywood, the decrease in MFA from ca. 9.5° in the ring 5 to 4.5° in the ring 60 so by 5° is accompanied by a 66% increase in the specific tensile strength (from 12 to $20 \cdot 10^{-4}$ m^2/s^2) and 36 increase in the modulus of elasticity (from 1540 to

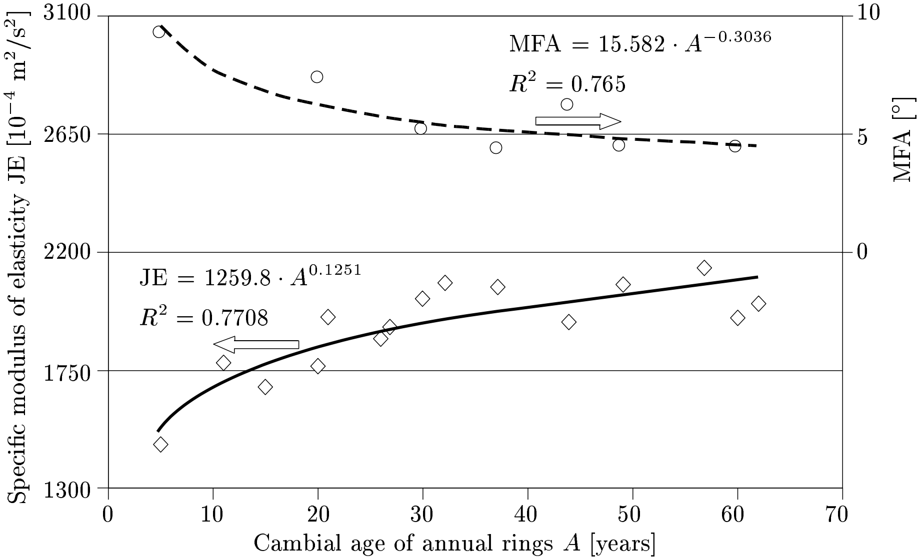

Fig. 5. Specific modulus of elasticity and mean MFA in earlywood as the functions of cambial age of annual rings

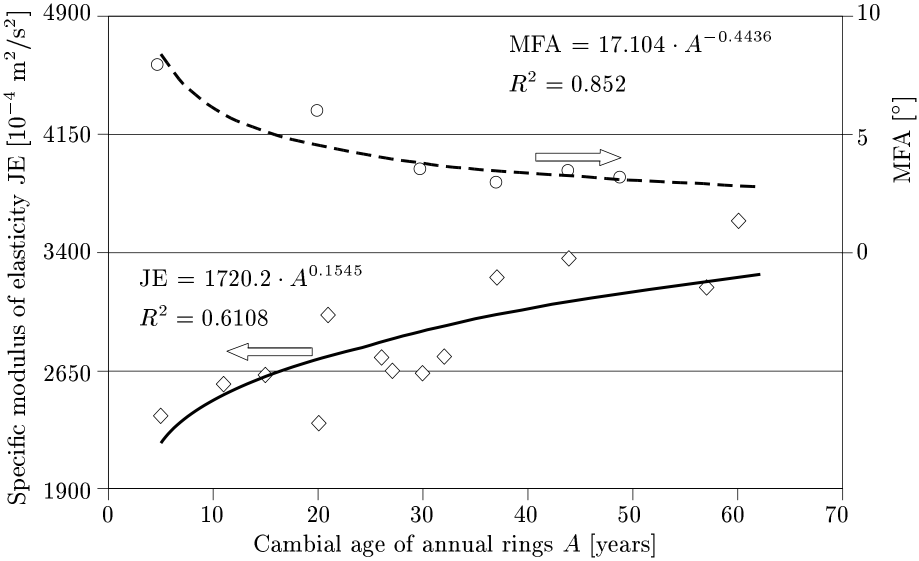

Fig. 6. Specific modulus of elasticity and mean MFA in latewood as the functions of cambial age of annual rings

$2100 \cdot 10^{-4}$ m^2/s^2). The influence of MFA is even more pronounced for latewood. When MFA decreases from 8.4° to 2.8°, the accompanying increase in the specific tensile strength of latewood is from 14 to $32 \cdot 10^{-4}$ m^2/s^2, so over two times. In this range of MFA variation the specific modulus of elasticity increased by almost 50%. The character of the above changes indicates a clear relationship between the specific tensile strength and modulus of elasticity and MFA. The relation between the specific tensile strength and MFA is presented in Figure 7. In the MFA range considered this relation can be approximated by a square function. Taking into regard the fact that MFA values are mean values determined only on tangent cell walls, the correlation coefficient characterising the above relation R^2 close to 0.7, should be treated as very high. The relation seems universal as the specific tensile strength as a function of MFA in early and latewood is described by the same function. This value of the correlation coefficient follows also from the fact that MFA change in a relatively wide range, (Table 1), so the rigidity and strength of cell walls of even neighbouring tracheids can be much different. At a certain tensile stress, the most stressed walls are those in which MFA are the steepest (Reiterer et al. 1999, Groom et al. 2002, Moliński and Krauss 2008). It seems that for this reason a higher correlation can hardly be expected.

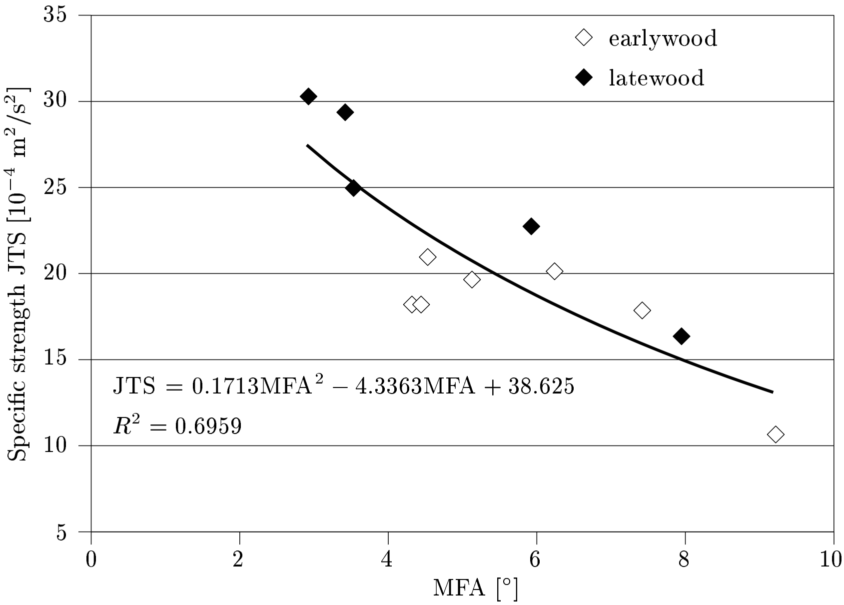

Fig. 7. The influence of MFA on specific tensile strength of wood measured along the grain

CONCLUSIONS

1. The density of spruce earlywood shows a clear tendency to decrease with increasing cambial age of annual rings, while the density of latewood increases up to the ring 30 and for older rings it remains unchanged up to the circumference. Hence, with growing maturity of wood its cyclic inhomogeneity increases.
2. With increasing cambial age of annual rings, the tensile strength and modulus of elasticity increase considerably.
3. The difference in spruce wood density within individual rings reaching 2.7 times is accompanied by a 5 times increase of the modulus of elasticity, so the wood density is not a reliable determinant of the wood mechanical properties.
4. The trends in the radial variations in the specific tensile strength and modulus of elasticity in early and latewood of spruce are practically mirror reflections of the MFA changes in these two growth zones.

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