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ORIGINAL

Surface modification of wood using friction

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Abstract The potential of linear vibration friction as an innovative means of producing increases in both surface density and surface hardness was explored. The influence of processing pressure and time on the degree of surface densification, surface hardness and surface elasticity was investigated. It was found that surface hardness (measured as Brinell hardness) was positively correlated with densification ratio. Furthermore, surface elasticity, that is the ability of the surface to recover elastically after indentation during the Brinell hardness test, could be increased by up to 33% depending on the degree of surface densification. The temperature rise due to friction was also studied. During processing, it was found that the temperature rise on both the radial and tangential surfaces was positively correlated with the processing pressure and time.

Introduction

By altering the characteristics of wood by, for example, resin impregnation accompanied by compression of the material, certain mechanical properties can be improved (Navi and Gigardet 2000; Gindl et al. 2004; Blomberg et al. 2005). Both impregnation and compression result in an increase in the density of wood that can lead to an improvement in its mechanical properties, in particular hardness (Navi and Gigardet 2000; Gindl et al. 2004; Zhang et al. 2006).

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Over the years several methods for increasing the density of wood through compression have been investigated and the strength properties of wood-based materials have been successfully enhanced by this approach (Ito et al. 1998; Navi and Gigardet 2000; Zhang et al. 2006). One of the prerequisites for this so-called ‘densification’ of the material to take place is that the wood material should be softened before compression. The softening behaviour of wood is affected by a number of factors that include moisture content, temperature, and the anatomical and chemical properties of the wood species being treated (Uhmeir et al. 1998; Navi and Gigardet 2000). It has been found, for example, that the glass transition temperature of water-saturated spruce lignin occurs at between 83 and 100°C (Salmén 1984) and in studies on the compressive behaviour of wood, it has been shown that the thermal softening of water-saturated spruce occurs at approximately 85°C, most probably due the glass transition temperature of lignin being reached (Uhmeir et al. 1998). Furthermore, compressive stress relaxation is negatively correlated with compression time and temperature (Dwianto et al.1998; Uhmeir et al. 1998). Thus, when thermally softened wood is compressed densification of the material is readily achieved.

Linear vibration friction technology (LVFT) is widely used in the plastics and automotive industries (Gfeller et al. 2004) and has been investigated as a means of bonding wood without adhesives (Gfeller et al. 2003). With LVFT, wood is joined together by the vibrational movement of one wood surface against another resulting in localised heating and softening of the wood material and as such it has the potential to induce local densification of wood surfaces. The results of preliminary testing have indicated that the surface hardness of wood can be doubled by this approach (Pizzi et al. 2005). Increasing the density of the surface only, rather than modifying the whole material, could be an advantage in applications where it is desirable to maintain the low bulk density of wood, yet improve the surface properties. LVFT offers the potential for targeted modification, increasing the surface density, and thereby the surface hardness of wood in a potentially cost-effective and controlled manner.

Surface densification by LVFT does not require the addition of chemicals. The energy needed to change the chemical/physical state of the wood is produced by friction parallel to the surface. It is well known that energy input is a function of the friction coefficient, the applied pressure, the type of surface as well as the amplitude, frequency and the vibration time. When the desired temperature is reached, the vibration movement is stopped and the pressure is maintained until the surface has solidified.

The overall objective of this study was to explore the potential of LVFT as a means of the industrial scale modification of wood. To achieve this aim, the influences of different process parameters on surface properties, such as hardness, were investigated. Herein, the effect of surface modification, produced using a modified linear vibration welding machine, on the surface hardness of wood are reported.

Materials and methods

Clear Norway spruce (*Picea abies*) with an average density of 0.45 g/cm^3 was utilised in this work. Specimens with dimensions of 305 × 20 × 30 mm^3 were machined such that the growth rings were oriented parallel to the 30 mm wide surface. After machining, the specimens were cut in two pairs of specimens with dimensions of 150 × 20 × 30 mm^3. One of the pairs was used as the reference specimen for hardness measurement and the other was subsequently modified as described below. In total 240 specimens were modified by densification. The specimens were conditioned for at least one month at RH 65% and 20°C prior to modification. Selected specimens were also treated with one thin layer of wax (3032, Osmocolor) or oil (1101, Osmocolor) prior to densification.

Densification

Modification was carried out on a suitably adapted Branson 2700 linear vibration welding machine. In essence, the equipment consisted of a lower, fixed, platen together with an upper platen able to vibrate linearly in a controlled manner. Pressure and heat could be applied to a specimen placed between the platens. The lower platen contained two 500 W heating elements plus four thermocouples for temperature sensing and a further one for controlling the heating elements. The wood specimen was fixed to the upper platen. The surfaces of the specimens were preheated to 100°C on the lower platen prior to densification.

Modification was carried out at a frequency of 100 Hz and an amplitude of 3 mm. Process pressure ranged from 0.63 to 1.55 MPa and the process time varied from 20 to 100 s (see Table 1). At the end of the vibration procedure, a constant pressure was maintained until the surface temperature had cooled down to 60°C. After modification the specimens were stored under standard conditions (RH 65%, 20°C) for at least 2 weeks prior to further testing.

Microscopy

Cross-sections, approximately 5 mm in thickness, were cut from the modified specimens and the surfaces were prepared by abrading with fine sandpaper. The transverse surfaces of the specimens were examined using a Leica DMLM reflecting microscope equipped with a Leica DFC 320 video camera.

Hardness, surface elasticity and densification ratio measurements

Measurements were conducted on a Zwick 1454 testing machine, equipped with a 2.5 kN load cell. A 10-mm diameter indenter was used for hardness measurement. Hardness measurement standards are seldom entirely suitable for wood-based materials and variations in the experimental setup are often made (Hirata et al. 2001; Niemz and Stübi 2000). Such adaptations are made because the density profile of wood materials or wood-based products is seldom homogenous and has a significant influence on hardness measurement. The Brinell hardness test used in this study was adapted from EN 1534 (2000) and JIS Z 2101 (1994). According to EN 1534 (2000), the load is constant and the diameter of the indentation is measured, whereas according to JIS Z 2101 (1994), the indentation depth is constant and the load is measured. In this study, the load was constant and the indentation

Table 1 Summary of process parameters and the maximum temperatures achieved

Series	Number of specimens	Process pressure (Mpa)	Process time (s)	Temperature (max) (°C)
SR	10	0.63	40	156
SR	10	0.63	50	193
SR	10	0.77	20	138
SR	10	0.77	35	158
ST	10	0.77	40	148
ST	10	0.77	100	167
ST	10	1.55	50	189
ST	10	1.55	20	158
SRO	10	0.87	40	178
SRO	10	0.87	80	162
SRO	10	1.3	40	228
SRO	10	1.3	30	152
STO	10	0.77	50	205
STO	10	0.77	70	152
STO	10	1.1	30	178
STO	10	1.1	60	167
SRW	10	0.87	40	176
SRW	10	0.87	80	166
SRW	10	1.3	40	182
SRW	10	1.3	30	150
STW	10	0.77	50	201
STW	10	0.77	70	187
STW	10	1.1	30	170
STW	10	1.1	60	157

S spruce, *R* radial grain orientation, *T* tangential grain orientation, *O* oiled surface, *W* waxed surface

depth was measured. The Brinell hardness H_B (N/mm^2) was calculated using Eq. 1 where D (mm) is the diameter of the indenter, h (mm) the maximum depth of the indentation and F (N) the applied load.

$$H_B = \frac{F}{\pi \times D \times h} \tag{1}$$

The maximum load was 300 N and the loading speed 20 N/s. The maximum load was maintained for 25 s prior to unloading at a speed of 20 N/s. The maximum depth, h_{max}, of the indentation was measured and also the elastic deformation, h_e, of the indentation. The elastic deformation was measured as the ‘immediate’ recovery of the indentation when the load was removed. The value h_e was measured when the load reached zero during unloading. Four measurements on each of the treated and untreated specimens were taken. The procedure for calculating the surface elasticity was adapted from earlier studies by Niemz and Stübi (2000). The surface elasticity, ε_e, was calculated using Eq. 2.

$$\varepsilon_{\mathrm{e}} = \frac{h_{\max} - h_{\mathrm{e}}}{h_{\max}} \tag{2}$$

The densification ratio, compression set, C, was calculated using Eq. 3 where T_0 andT_{C} are the thickness of the specimen before and after densification, respectively.

$$C = \frac{T_0 - T_{\mathrm{C}}}{T_0} \tag{3}$$

The thickness of the specimen was measured prior to and immediately after densification, using a dial indicator (average of two measurements per specimen), from which the densification ratio was calculated.

Results and discussion

The process parameters were chosen in such a way that the surface temperature rose to around either 150 or 200°C using different combinations of process pressure and time. It was, however, found that controlling the temperature was difficult, probably due to the heterogeneous structure of the wood. Therefore, the actual temperatures differed significantly from the desired ones. The process parameters and maximum temperatures generated are presented in Table 1.

The increase in surface temperature during processing was investigated on surfaces that had been abraded with fine sandpaper so as to minimise differences in the coefficient of friction. As can be seen from Fig. 1, the temperature generated increased with process time. Furthermore, the temperature rise was more rapid at higher process pressures. After approximately 20 s, the temperature rise followed a power equation. It was found that the temperature difference between tangential and radial surfaces was small at high process pressures (1.39 MPa), but with a low (0.67 MPa) process pressure the difference was significant. The influence of the surface characteristics of wood probably has a greater influence on frictional heat generation when the process pressure is lower.

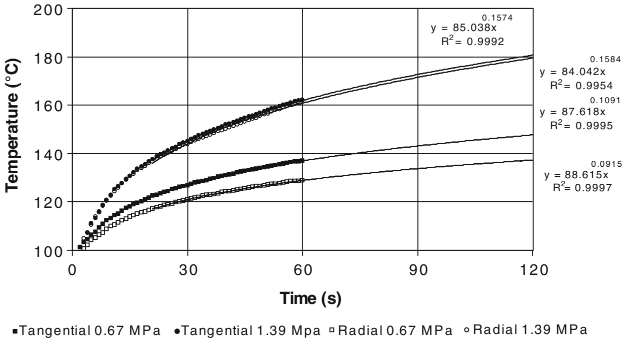

Fig. 1 The temperature rise with low (0.67 MPa) and high (1.39 MPa) process pressures on tangential and radial annual ring orientation. Temperature rise in 60 s on sanded surfaces followed by extrapolation to 120 s

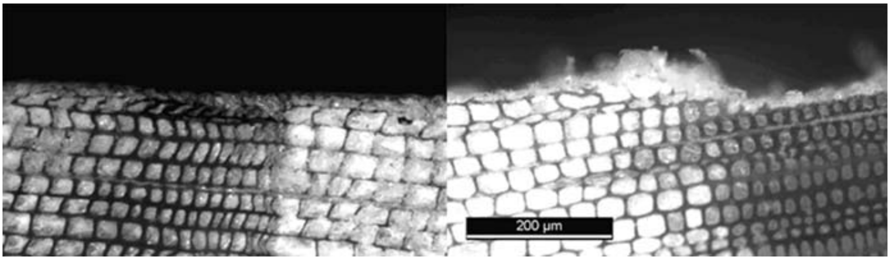

Fig. 2 Densified surface on the *left* side and original surface after preparation with a circular saw on the *right* side

Figure 2 shows the modified and unmodified cross-sections of specimens densified in the tangential direction (i.e., the radial surface). The treated surface was densified at a process pressure of 0.78 MPa resulting in a low densification ratio. It can be seen that only the first layer of cells has been affected by the densification treatment. The treated surface, however, appears to be much smoother. Figure 3 shows the cross-section of a specimen densified radially. This specimen was densified at a pressure of 1.39 MPa. As may be observed, only the early wood has been densified on the top of the specimen as well adjacent to the late wood. A more detailed microscopy study will be reported in a subsequent publication.

Brinell hardness and elastic recovery

The average Brinell hardness of unmodified spruce was found to be 12 N/mm^2 on the radial surface and 9 N/mm^2 on the tangential surface (an average of 160 measuring spots on both series). Hardness is significantly higher in latewood than in earlywood (Hirata et al. 2001) due to the differences in densities. This phenomenon affects the hardness of the radial and tangential surfaces; on the radial surface the

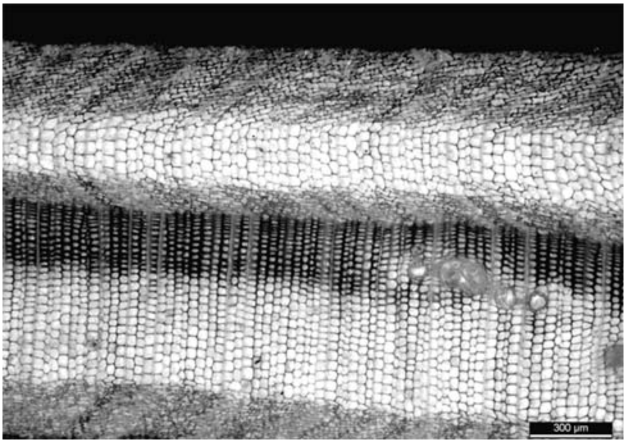

Fig. 3 Cross-section of densified specimen (tangential surface) with process pressure of 1.39 MPa

latewood acts as ‘reinforcement’ resulting in greater hardness. On the tangential surface, however, the earlywood leads to greater flexibility. As shown in Figs. 4 and 5, Brinell hardness was found to increase with increasing densification ratio. It is clear that by compressing the wood material the density increases, thus the hardness increases. However, even if the wood is compressed by less than 1 mm (from 30 mm original thickness), hardness is still improved. This indicates that the surface (the first cell layers) has a significant effect on surface hardness.

The densification ratio range on the tangential surface was 1–9% and on the radial surface 1–4%. The difference in the densification ratios of the radial and tangential surfaces is most likely caused by the higher energy input needed to achieve the target temperatures on the different surfaces. Furthermore, the aforementioned ‘reinforcement’ effect provided by the latewood probably resists

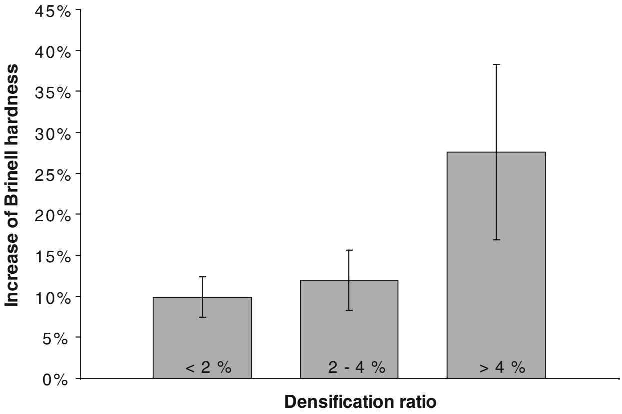

Fig. 4 Effect of densification ratio on the hardness of the radial surface. The confidence interval for the mean at a confidence level of 95% is shown

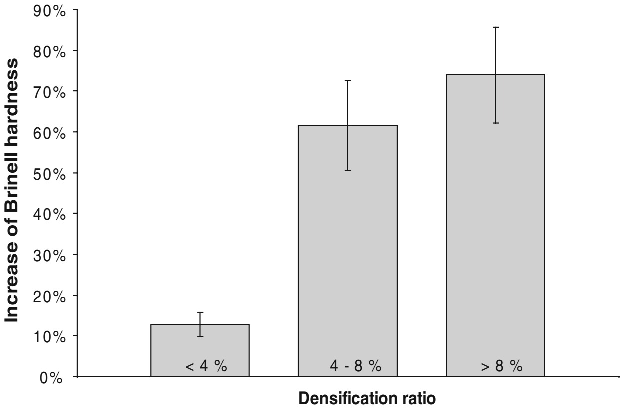

Fig. 5 Effect of densification ratio on the hardness of the tangential surface. The confidence interval for the mean at a confidence level of 95% is shown

compression to a greater extent on the radial surface than on the tangential surface, resulting in more energy being needed to achieve the same level of densification on the radial surface as on the tangential surface. In an earlier study by Navi and Gigardet (2000), spruce wood was compressed by 68% resulting in Brinell hardness values that were significantly higher (more than 60 N/mm^2) than the values reported in this work. In this work, however, there was no clear evidence of a correlation between process pressure and Brinell hardness, probably due to the many interacting variables influencing the results.

The elastic deformation of the surface is an important property which is seldom mentioned when Brinell hardness is reported. According to EN 1534 (2000), the Brinell hardness should be calculated from the diameter of the indentation 3 min after removal of the load. Thus, according to EN 1534 (2000), the elastic recovery is already accounted for by the Brinell hardness value. The elastic deformation indicates how much the indentation recovers after the hardness test. The elastic recovery of the surfaces was found to be significantly higher, by up to 33%, when the surface has been densified (Fig. 6). It is probable that this phenomenon is due to a combination of thermally induced chemical changes in the wood material and resins which have bled from the specimen. Furthermore, the microstructure of the densification of the cells could cause an increase in the elastic recovery.

The influence of surface treatment on the surface densification process

A number of specimens were oiled or waxed before densification in order to investigate their influence on the densification process. The treatments decrease the friction on the surface, thus the process time needs to be longer to generate a high enough temperature. The oil and wax treatments increase the positive appearance of

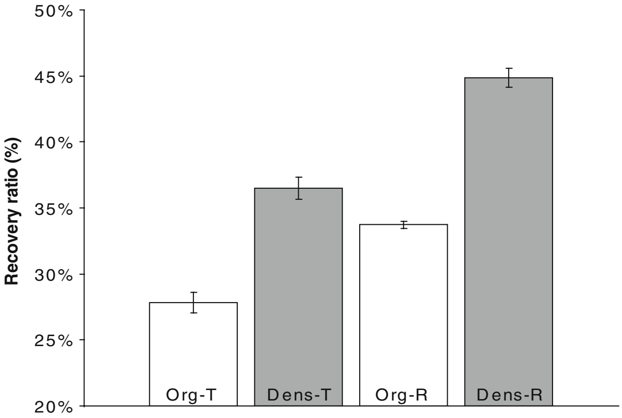

Fig 6 Elasticity of the surface. Org-T is the value of the original specimens which have tangential grain oriented surfaces. Org-R is the value of the original specimens which have radial grain orientation. *Dens*, densified specimens. The confidence interval for the mean at a confidence level of 95% is shown. The specimens have been oiled or waxed prior to the process. Unfortunately, there are no results of non-treated specimens

the densified surface. The colour of the modified surface did not change significantly from the original, and colour change was not quantified.

Conclusion

Linear vibration friction technology is suitable for the surface densification of spruce. Densification of wood always needs a certain amount of energy input which, in this technology, is generated by the friction between wood and a metal plate. Softwood such as spruce is easier to densify on the tangential surface than in the radial surface because of the structural properties of the wood. It was found that the minimum processing pressure was between 1 and 1.3 MPa in order to develop a suitable densification ratio in a time that was not too long. The Brinell hardness was found to correlate well with the densification ratio. One of the most interesting features in the process is that the LVFT increases the surface elasticity by up to 33%.

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