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Influence of grain direction in vibrational wood welding

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Abstract

Wood grain orientation differences in the two surfaces to be bonded yield bondlines of different strength in no-adhesives wood welding. Longitudinal wood grain bonding of tangential and radial wood sections yields an approximately 10% difference in strength results of the joint. Cross-grain ($\pm 90°$) bonding yields instead a much lower strength result, roughly half that observed for pieces bonded with the grain parallel to each other. These differences can be explained by the very marked effect that homogeneity of fibre orientation is known to have on fibre–matrix composites. Oak yields lower results than beech and maple and is more sensitive to welding conditions. Differences in both anatomical and wood constituent composition can account for this difference in performance. Contrary to the other wood species, oak always presents joint bondlines where little or no increase in density at the interface is noticed. This explains its somewhat lower strength results. This is based on the different mode of bonding predominant in this species, while the other species present two different modes of bonding. Thus, two types of bondlines are observed by scanning electron microscopy (SEM): (i) bondlines where entangled fibre–matrix composites are formed at the interface and (ii) bondlines in which direct welding of the cell walls occurs, just by fused intercellular material or cell surface material. In this latter case the cells remain flat, without an entangled fibre–matrix composite being formed. This is the almost exclusively predominant case for oak. Both cases and even hybrid cases between the two have also been observed in beech.

Keywords: bonding modes; wood grain; wood melting; wood welding.

Introduction

Mechanically induced wood flow welding, without any adhesive, rapidly yields structural grade-strength wood joints (Gfeller et al. 2004). It is due mostly to the melting and flowing of the amorphous materials interconnecting wood cells, mainly lignin and some hemicelluloses (Gfeller et al. 2004). This causes the partial detachment, the "ungluing" of long wood cells and wood fibres, and the formation of an entanglement network in a matrix of melted material that then solidifies. A wood cell–fibre entanglement network composite is then formed having a molten lignin polymer matrix.

Adhesion of wood surfaces by vibration welding is accompanied by a considerable increase in the density of the wood at the bonded interface (Leban et al. 2004). This is due to the loss of the intercellular structure of the wood at the interface and considerable decrease of empty spaces in its cellular structure. The sharper and more regular the increase in density is at the interface, the better the mechanical performance of the joint (Leban et al. 2004). X-ray microdensitometry is the technique most apt to observe the different occurrences of a welded wood interface (Leban et al. 2004). This is so even in the most difficult case of rotational high-speed welding of dowels in which grain direction is completely variable (Pizzi et al. 2004). For this reason, it is again used extensively in the work presented here.

The work presented here is aimed at (1) determining the limits of the present technique as regards the relative wood grain orientation of the wood specimens to be bonded. Thus, tangential, radial, and cross-fibre directions of the two surfaces to be welded were tested. (2) The strength variation obtained from three hardwoods of different characteristics – namely, beech, oak, and maple – were tested.

Methods

Preparation of joints by mechanically induced wood welding

Specimens were composed of two pieces of tangential, radial, and cross-fibre (90°) beech (*Fagus sylvatica*) wood by exerting a vibrational movement of a wood surface against the other at a frequency of 100 Hertz. The specimens of $150 \times 20 \times 15$ mm dimensions were welded together to form a bonded joint of $150 \times 20 \times 30$ mm. Ten specimens were welded for each case. When the fusion state was reached at the joint interface, the vibration process was stopped. The clamping pressure was then briefly maintained until the bond solidified. The welded samples were conditioned for 1 week in a climatic chamber (20°C and 65% moisture content [MC]) before testing.

The species of hardwood compared were beech (*Fagus sylvatica*), oak (*Quercus robur*), and maple (*Acer* spp.). The equilibrium MC of the samples was 12%.

Welding was carried out on wood whose surface had been smoothed by planing in order to compare it with previous work (Gfeller et al. 2004) where sanding was used.

The parameters used for welding were those optimised previously (Gfeller et al. 2004): the welding time (WT) was varied (WT = 3, 4, and 5 s). The contact holding time (HT) was maintained at 5 s after the welding vibration stopped. The welding pressure (WP) exerted on the surfaces was maintained at

Table 1 Tensile shear strength mean values and standard deviations tests according to European standard EN 204 (2004) and method EN 205 (2003) of mechanically induced wood fusion welding (each result is the average of 10 tests).

			Welding time		
			3 s (N mm^{-2})	4 s (N mm^{-2})	5 s (N mm^{-2})
Beech	radial section	fibres longitudinal	8.2±0.8	8.0±1.0	7.6±1.2
	tangential section	fibres longitudinal	9.0±1.3	9.4±1.6	8.2±1.4
	radial cut	90° crossed fibres	4.2±0.4	3.9±0.4	3.7±0.3
	radial section	planed	8.2±1.9	8.0±2.9	7.6±2.7
Oak	radial section	planed	7.5±1.6	5.8±3.0	3.1±2.0
Maple	radial section	planed	10.7±2.4	10.6±1.5	9.2±2.0

1.3 MPa. The holding pressure (HP) exerted on the surfaces after the welding vibration stopped was maintained at 2.0 MPa. The amplitude of the shift imparted to a surface relative to the other during vibrational welding was maintained at 3 mm. The frequency of welding was maintained at 100 Hz.

The tensile shear strength was measured according to European standard EN 204 (2004) and method EN 205 (2003). Saw cuts perpendicular to the specimen's wood grain, down to the bondline, were made from each one of the specimen's two surfaces. The distance between the two cuts was 2.5 cm. The specimens were then tested under tension on an Instron 4467 universal testing machine at a rate of 2 s/mm.

X-ray microdensitometry

The X-ray microdensitometry equipment used consisted of an X-ray tube producing "soft rays" (low energy level) with long-wave characteristics emitted through a beryllium window. These were used to produce an X-ray negative photograph of approx. 2-mm thick samples, conditioned at 12% MC, at a distance of 2.5 m from the tube. This distance was important to minimise blurring of the image on the film frame (18×24 cm) used. The usual exposure conditions were 4 h, 7.5 kW, and 12 mA. Two calibration samples were placed on each negative photograph in order to calculate wood density values. The specimens were tested in this manner on equipment consisting of an electric generator (INEL XRG3000), an X-ray tube (SIEMENS FK60-04 Mo, 60 kV–2.0 kW), and a KODAK film negative Industrex M100.

Scanning electron microscopy

Scanning electron microscopy (SEM) of (1) the surface of the open joints after mechanical testing and (2) the waste fibre that accumulated on the surface of the joints during welding was performed after metallizing the specimens with gold-palladium. The SEM equipment used was a Hitachi S-520.

Results and discussion

Physical properties

The results shown in Table 1 indicate that, for bonding along the longitudinal wood grain, slightly better results are obtained for the tangential versus the radial section. This is only a trend because the differences noted, although consistent, are not statistically significant. Both 3-s and 4-s welding times yield the best results. At the 5-s welding time, the results start to become lower, confirming previous findings (Gfeller et al. 2004). Statistically significant differences do, however, exist between these specimens and those bonded at 90° crossed wood grains of the two surfaces (Figures 1 and 2). The crossed wood grain specimens (typical example shown in Figure 1) yield much lower bond strengths. However, the results obtained are still very acceptable for many interior applications. They also present much lower variability. For cross-grain-bonded specimens, the bond strength decreases slightly with lengthening welding time, as expected. The best results are obtained for the 3-s welding time. European standard EN 204 (2004) and testing method EN 205 (2003) for thermoplastic adhesives were chosen for the test rather than EN 301 (1993) and EN 301-1 (1993) for thermosetting adhesives. This was done because wood welding is exclusively used for interior furniture and joinery, hence as a substitute for PVAc, a thermoplastic adhesive.

Effect of grain angle and fibre orientation

The bondline has been observed as being composed of entangled fibres immersed in a matrix of molten com-

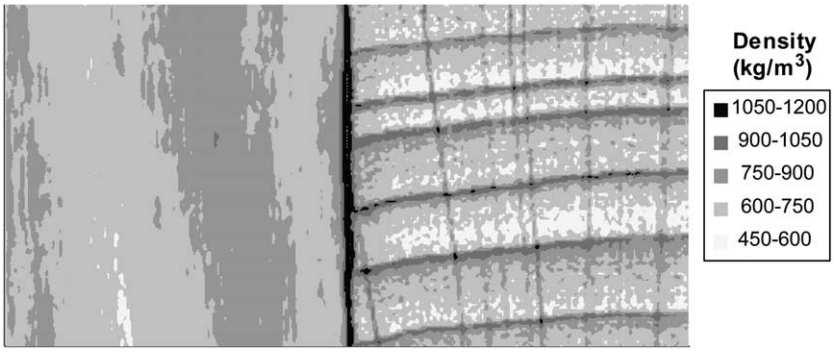

Figure 1 X-ray microdensitometry-obtained density map of welded joint from cross-fibres of beech specimens.

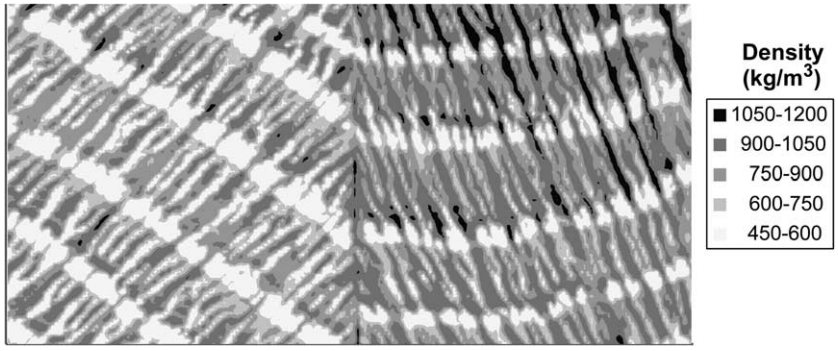

Figure 2 X-ray microdensitometry-obtained density map of welded joint from radial section of oak specimens.

pounded middle lamella material (Gfeller et al. 2004; Leban et al. 2004). The comparative results of radial, tangential, and cross-fibre strength in Table 1 indicate that grain angle and fibre orientation are important in wood welding. Passing from the standard bonding of radial sections (Gfeller et al. 2004) to bonding tangential sections, grain angle and hence fibre orientation of the two surfaces change slightly. As a consequence, fibre orientation in the interfacial high-density composite also changes slightly. The orientation of the fibres in relation to the testing force applied to it has a very marked influence on the strength of a fibre–matrix composite (Kocks et al. 2000). Even very minor variations in fibre orientation angle cause very marked strength differences in the composite (Kocks et al. 2000). Thus, the very small change in fibre orientation passing from bonding radial sections to bonding tangential sections yields some improvement in the strength results. Equally, in the cross-fibre case, because relative fibre orientation in the composite is considerably more affected and less homogeneous, the mechanical resistance of the joint is lower (Table 1).

Bondline appearance and bonding mode

Two types of morphology of the welded bondlines are observable by scanning electron microscopy: (i) bondlines in which higher density entangled fibre–matrix composites are formed and for which photographic evidence has already been given (Gfeller et al. 2004); (ii) bondlines in which direct welding of the cell walls of a surface to the cell walls of the other surface by the molten cell surface or intercellular material is observed. In these, the wood cells remain flat, and an entangled fibre–matrix composite does not constitute the bondline. Thus, Figure 3A,B shows oak welded bondlines that have been separated and where quite evidently the cell walls of a surface have bonded to the fused material of the cell wall of the second surface, without any entanglement. In the case of oak, this shallower case is almost exclusively the predominant one. This explains the small or no increase in interface density observed and the lower bond strength obtained. In the case of beech, cases (i) and (ii) are equally present; whenever a small anatomical gap between the two surfaces occurs, then case (i) predominates. Hybrid cases also occur, in which the cells of a surface remain flat and their walls bond to the entangled fibre–matrix composite.

X-ray microdensitometry and bondline density

Several parameters appear to be in direct relation to the bond strength obtained. These are the interfacial composite density as measured by X-ray microdensitometry, the evenness of the bondline (Leban et al. 2004), and the evenness of the grain of the wood species used. This can be seen from the comparison of the bond strength results of planed radial sections of beech, oak, and maple in Table 1. Maple specimens, the most even-grained of the three species, give a smoother bondline than the equivalent beech specimens. Conversely, while the bondline in oak (typical example in Figure 2) appears to be equally smooth, the bondline density is much lower (Figure 2; no extensive dark line can be observed at the interface). This indicates a lower density composite at the interface, consistent with the lower oak bond strength in Table 1. However, for oak, contrary to beech and maple, the dependence of the bond strength on the welding time is considerable and statistically significant (Table 1). For oak, a 3-s welding time gives the best bond strength result, and the bond strength markedly decreases with lengthening welding time.

Anatomical and wood constituent influences in wood welding

Figure 2 shows that the oak interface (bondline) is not any denser than the two bonded wood pieces. The effect cannot be due to oak being more sensitive to degradation following more extensive and rapid charring at the interface. Rather, it seems to be due to the extreme shallowness of the interface composite formed. Once formed, to prolong the welding time means only to disturb and destroy the small amount of fibre entanglement giving the bond (Gfeller et al. 2004). This leads to the marked decrease in bond strength shown in Table 1. The differences leading to this could be anatomical or chemical.

The poorer welded strength results for oak indicate that the anatomy of the wood species, hence its microroughness, may have an influence on the friction coefficient. Thus, it has an influence on the maximum temperature that can be reached during welding and consequently on the quality of welding. Oak specimens always give the impression of low or no friction and of the two surfaces just sliding against each other without wood fibres detaching from the surfaces.

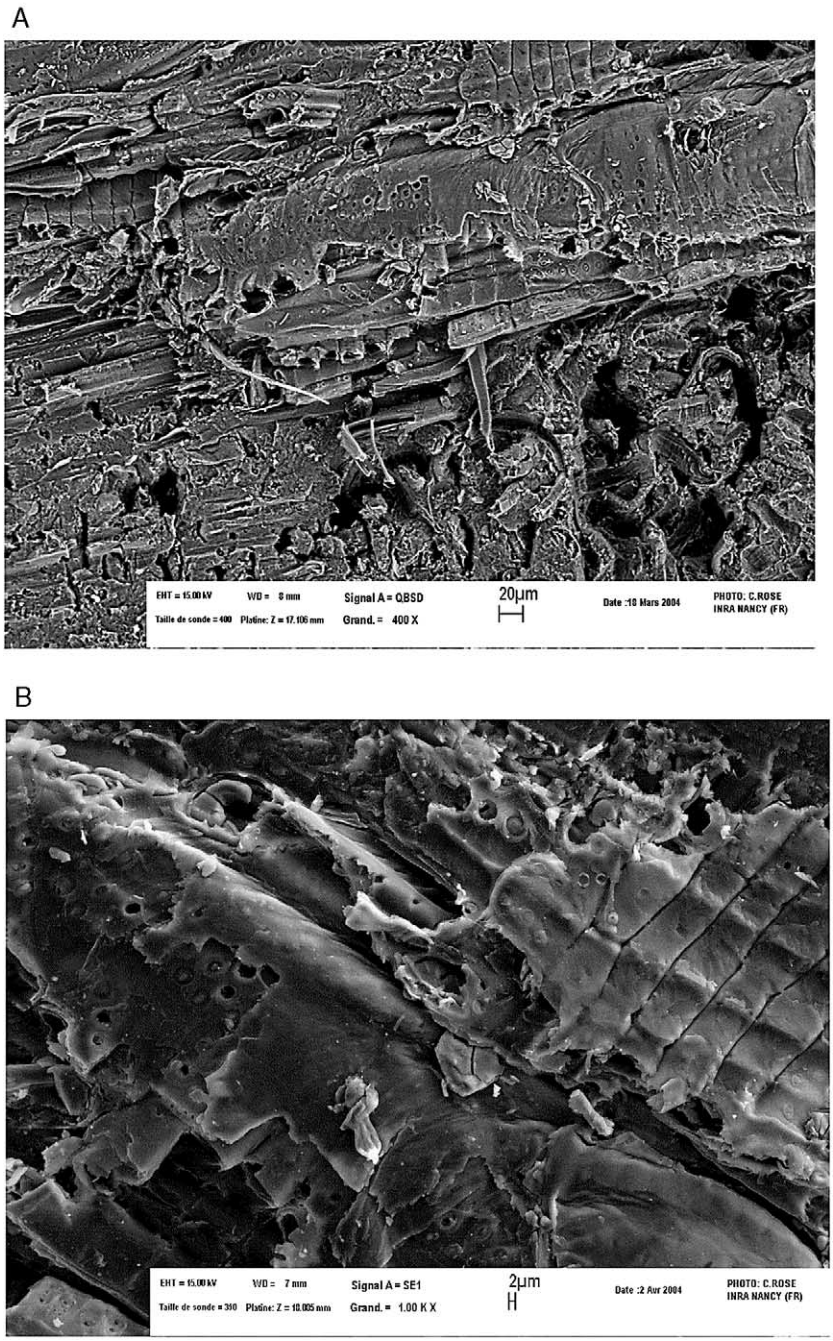

Figure 3 Oak welded bondline in which (A) direct welding of the cell walls is observable with the cells remaining flat, and where entangled fibre–matrix composites do not constitute the bondline. This is the predominant mode in oak. (B) Higher magnification detail of (A) in which the peeling of the oak cell walls can be observed.

Alternatively, the lignin/hemicelluloses of oak's middle lamella may not flow as easily. This implies perhaps a higher molecular weight or a different type of lignin; hence, oak middle lamella presents a lower proportion of material that can flow. It can also imply that heat transfer is poorer in denser wood, thus flowing is not as rapid as in other species.

That the composition of the middle lamella has an effect on the results in Table 1 is evident by the typical analysis values for the three wood species. Typical results obtained for lignin and polyoses analysis of the three types of wood (Fengel and Wegener 1989) show that the typical level of lignin in maple is 22.8% (Browning and Isenberg 1952). This is comparable to the lignin levels reported for beech at 22.2% (Fengel et al. 1979), 22.8% (Lal et al. 1977), and 23.8% (Kürschner and Melcherova 1965). The values reported for oak are instead much higher at 24.9% (Bednar and Fengel 1974) and 29.6% (Wagenführ and Scheiber 1974). Conversely, for the total polyoses, the typical values reported by the same authors for the three wood species are, respectively, 26.5% for maple; 50.8%, 44.4%, and 36.5% for beech; and finally 38.8% and 22.2% for oak. Although these values refer to the whole timber, it is noticeable that some correlation trend exists between the total amount of lignin and the results in Table 1. Thus, beech and maple give the best results with a comparable amount of lignin, and oak gives a lower result with a higher level of

lignin. No obvious correlation between polyoses level and Table 1 results is noticeable.

Conclusions

Mechanically induced vibration welding of wood can yield bondlines of different strength according to the wood grain orientation in the two surfaces to be bonded. Thus, longitudinal grain bonding of tangential and radial wood sections gives different strength results of the joint, although such a difference is not excessive and is limited to roughly 10%. Cross-grain bonding, hence bonding of radially cut sections, with the longitudinal wood grain of the two surfaces at a 90° angle to each other, yields much lower strength. This is about half that observed for pieces bonded with the grain parallel to each other. These differences can be explained by the law of fibre–matrix composites and by the very marked effect that homogeneity of fibre orientation is known to have on such composites. Oak has been found to yield lower results than beech and maple and to be more sensitive to welding conditions. Differences in both anatomical and wood constituent composition can account for this difference in performance. Furthermore, oak always presents joint bondlines where little or no increase in density at the interface is noticed. This is based on the different mode of bonding predominant in this species, while the other species present two different modes of bonding. Thus, both entangled fibre–matrix composite bondlines and direct welding of flat cell to flat cell occur. The latter is the predominant case for oak. Both cases and even hybrid cases between the two have also been observed in beech.

References

Bednar, H., Fengel, D. (1974) Physical, chemical, and structural properties of recent and subfossil oak wood. Holz Roh-Werkst. 32:99–107.

Browning, B.L., Isenberg, I.H. (1952) Analytical data and their significance. In: Wood Chemistry. Eds. Wise, L.E., Jahn, E.C. 2nd Edition, Vol. 2. Reinhold Publ. Corp., New York. pp 1259–1277.

European Standard (2004) EN 204, Classification for thermoplastic adhesives.

European Standard (2003) method EN 205, Determination of the tensile strength.

European Standard (1993) EN 301, Classification for adhesives: phenolics and aminoplastics.

European Standard (1993) EN 301-1, Tensile strength.

Fengel, D., Wegener, G. Wood – Chemistry, Ultrastructure, Reactions. De Gruyter, Berlin, 1989.

Fengel, D., Uçar, H., Wegener, G. (1979) Isolation and characterization of the polysaccharides from beechwood (*Fagus sylvatica* L.). Papier 33:233–239.

Gfeller, B., Pizzi, A., Zanetti, M., Properzi, M., Pichelin, F., Lehmann, M., Delmotte, L. (2004) Solid wood joints by *in situ* welding of structural wood constituents. Holzforschung 58:45–52.

Kocks, J.F., Tome, C.N., Wenk, H.R. Texture and Anisotropy, Cambridge University Press, 2000.

Kürschner, K., Melcerova, A. (1965) Chemical changes occurring in beechwood on thermal treatment. I. Chemical changes in sawdust during 1–28 day heating at 80–160°. Holzforschung 15:15–18.

Lal, N.K., Butnaru, R., Simionescu, C. (1977) Investigations in the field of chemical and morphological structure of certain tropical woodspecies. Part 2: The study of their chemical composition. Cell. Chem. Technol. 11(1):59–66.

Leban, J.-M., Pizzi, A., Wieland, S., Zanetti, M., Properzi, M., Pichelin, F. (2004) X-Ray microdensitometry analysis of vibration-welded wood. J. Adhesion Sci. Technol. 18(6):673–685.

Pizzi, A., Leban, J.-M., Kanazawa, H., Properzi, M., Pichelin, F. (2004) Wood dowels bonding by high speed rotation welding. J. Adhesion Sci. Technol. 18(11):1263–1278.

Wagenführ, R., Scheiber, C. Holzatlas. VEB Fachbuchverlag, Leipzig, 1974.

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