J. Adhesion Sci. Technol., Vol. 18, No. 6, pp. 673–685 (2004)

X-ray microdensitometry analysis of vibration-welded wood

J.-M. LEBAN [1], A. PIZZI [2,*], S. WIELAND [3], M. ZANETTI [2], M. PROPERZI [3] and F. PICHELIN [3]

[1] *INRA, Institut National de la Recherche Agronomique, Centre de Champenoux, F-54280 Champenoux, France*
[2] *ENSTIB-LERMAB, University of Nancy 1, BP 1041, F-88051 Epinal Cedex 9, France*
[3] *SWOOD, Swiss School of Engineering for the Wood Industry, Solothurnstrasse 102, CH-2504 Biel, Switzerland*

Received in final form 9 March 2004

Abstract—X-ray microdensitometry tests on vibration-welded hardwoods (beech and oak) and a softwood (spruce) showed that adhesion of wood surfaces by vibration welding was accompanied by a considerable increase in the density of the wood at the bonded interface. 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 is the increase in density at the interface the better is the mechanical performance of the joint. This was ascribed to the marked difference in wood density between earlywood and latewood. This intra-ring wood heterogeneity is a limiting factor for reaching high local compression rates during the welding process. In the case of spruce wood it causes cells collapse and, consequently, poorer bonding. Absolute and relative density maps of well-bonded, poorly-bonded and unbonded joints are reported. X-ray microdensitometry proved to be a valuable technique to determine the extent of wood welding.

Keywords: Wood welding; wood fusion; polymer melting; adhesives; lignin; joints; X-ray microdensitometry.

1. INTRODUCTION

Mechanically-induced friction welding techniques which are widely used in the plastic and automotive industries have recently also been applied to joining wood, without the use of any adhesive [1]. These techniques work by melting some wood components and forming at the interface between the two wood surfaces to be joined a composite of entangled wood fibres drowned into a matrix of molten wood

*To whom correspondence should be addressed. Tel.: (333) 2929-6117. Fax: (333) 2929-6138. E-mail: pizzi@enstib.uhp-nancy.fr

intercellular material, such as lignin [1]. Linear mechanical friction vibration has been used to yield wood joints satisfying the relevant requirements for structural applications by welding at a very rapid rate [1]. Cross-linking chemical reactions also have shown to occur by CP-MAS ^{13}C-NMR. These reactions, however, are relatively minor contributors during the very short welding period but acquire more importance after the welding period [1].

Wood density is often one good estimator of other wood physical and mechanical properties. X-ray microdensitometry is a technique used to investigate solid wood density distribution [2–11], and has been adapted and applied for quantitative analysis of intra-ring wood density variations [2, 3, 8, 9]. It has been used to study higher or lower density zones in solid wood, such as wood growth rings [2–11].

This paper deals with the application of X-ray microdensitometry to the joints formed by vibration welding for different wood species and with the correlation of joint performance with the microdensitometry map obtained for the joint by this analysis technique.

2. EXPERIMENTAL

The mechanical welding machine used was a Branson welding machine, type 2700, 100 Hz, normally used to vibrationally weld metals.

2.1. Preparation of joints by mechanically-induced wood fusion welding and their testing

Specimens composed of two pieces of beech (*Fagus sylvatica*), a hardwood, of Norway spruce (*Picea abies*), a softwood, and of oak (*Quercus robur*), a higher-density hardwood, each measuring 150 × 20 × 15 mm were welded together to form bonded joints measuring 150 × 20 × 30 mm by a vibrational movement of one wood surface against another at a frequency of 100 Hz. Ten welded specimens for each type of wood were prepared. When the fusion and bonding were achieved, the vibration process was stopped. The clamping pressure was then briefly maintained to optimize bonding [1]. The welded samples were conditioned for one week in an environmental chamber (20°C and 65% RH) before testing.

The parameters used were those optimized in the preceding study [1], namely a welding time (W.T.) of 3 s; a pressure holding time (H.T.) after welding of 5 s; a welding pressure (W.P.) exerted on the surfaces of 1.3 MPa; a holding pressure (H.P.) exerted on the surfaces after the welding vibration had stopped of 2.0 MPa; and an amplitude (A.) of the shift imparted to one surface relative to the other during vibrational welding of 3 mm. The frequency of welding was maintained at 100 Hz. The equilibrium moisture content of the samples was 12%.

Three sections were obtained from each of these samples and tested by X-ray microdensitometry. The sections were 1.88 ± 1 mm thick and their weight and density, respectively, were 0.79–0.85 g and 760–783 kg/m^3 for beech and 0.47–0.485 g and 496–511 kg/m^3 for spruce. Thus, a total of 30 sections per type of wood species were tested.

The wood-grain orientation of the two surfaces to be bonded has an influence, although not a determinant one. A comprehensive study on the effect of grain orientation on wood welding is in progress.

2.2. 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% moisture content, at a distance of 2.5 m from the tube. This distance is important to minimise blurring of the image on the film frame (18 $\times$ 24 cm) which was 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 an equipment consisting of an electric generator (Inel XRG3000), a X-ray tube (Siemens FK60-04 Mo, 60 kV, 2.0 kW) and a Kodak film negative Industrex type M100.

3. RESULTS AND DISCUSSION

In Fig. 1A and 1B X-ray microdensitometry images of two joints are shown, one of beech wood mechanically well welded (Fig. 1A) and the other of Norway spruce poorly welded (Fig. 1B). These images show clearly why spruce performs relatively poorly in relation to beech wood when mechanical wood welding is used. Beech joints are smooth when welded, while welded spruce joints have a very irregular interface. A similar irregular interface is always observed in spruce after any mechanical action, such as, for example, vacuum-pressure impregnation with wood preservatives, due to the phenomenon of wood cells collapse which is characteristic of this wood species. It is evident that in the case of spruce wood either mechanical welding is not possible to any great extent or the conditions of welding have to be markedly changed from those used for a hardwood such as beech. The three-dimensional map in Fig. 1C represents the beech joint in Fig. 1A. Figure 1C clearly shows that a marked increase in density has occurred at the mechanically-welded interface. This is one of the main causes of the joint’s high strength. Thus, from a density between 700 and 800 kg/m^3 of normal beech wood the welded interface reaches density values of 1000 kg/m^3, and even higher in some specimens. Wood strength is strongly density-dependent. The loss of the cellular structure in wood during mechanical welding with the consequent loss of the empty cellular spaces is the cause for this density increase. The increase in density at the welded wood interface and the wood density map of a joint are then measures of how good the joint is likely to be.

For each joint section, the density values were measured by centering one regular network of lines on the welded interface. This network consisted of 10 horizontal lines and 100 vertical lines. The average wood-density value is calculated at each intersection point between the above-mentioned vertical and horizontal lines. The horizontal resolution is, therefore, 0.3 mm while the vertical one is 2 mm. These wood-density values calculated by the CERD software are printed in one flat ASCII data file and can be displayed as illustrated in Fig. 1C. In this figure the vertical axis represents the wood density expressed in kg/m^3 while the two other axes represent

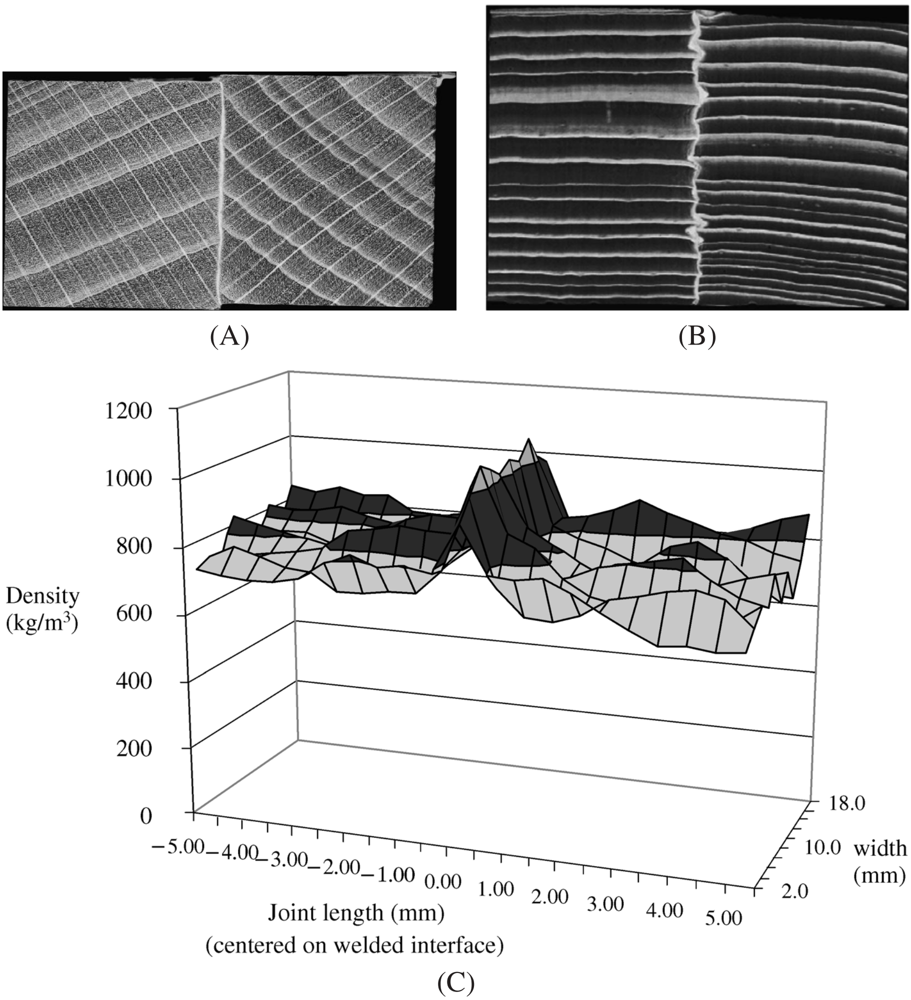


Figure 1. X-ray microdensitometry photographs of (A) well-bonded vibration-welded beech wood and (B) poorly-bonded vibration-welded Norway spruce wood. Note the fingerjointing effect in (B), due to spruce cellular collapse as a consequence of the wide difference in density of the latewood and earlywood growth rings of this species. (C) Three-dimensional wood density map of the well-bonded vibration-welded beech wood in (A).

the positions in the section as represented in Fig. 1A an 1B. In the middle of the sample, i.e. exactly on the welded bond, one can notice a strong increase in wood density value.

This increase in density is the result of the welding process itself and the assumption has been made that this increase in wood density can be seen as one quality criterion of the welding process. In order to illustrate the results, the wood density maps for two examples of beech and spruce have been reported in Fig. 2A and 2B. For each species the sections obtained are analysed in terms of wood density increase around the welded bond in order (i) to display the area where the

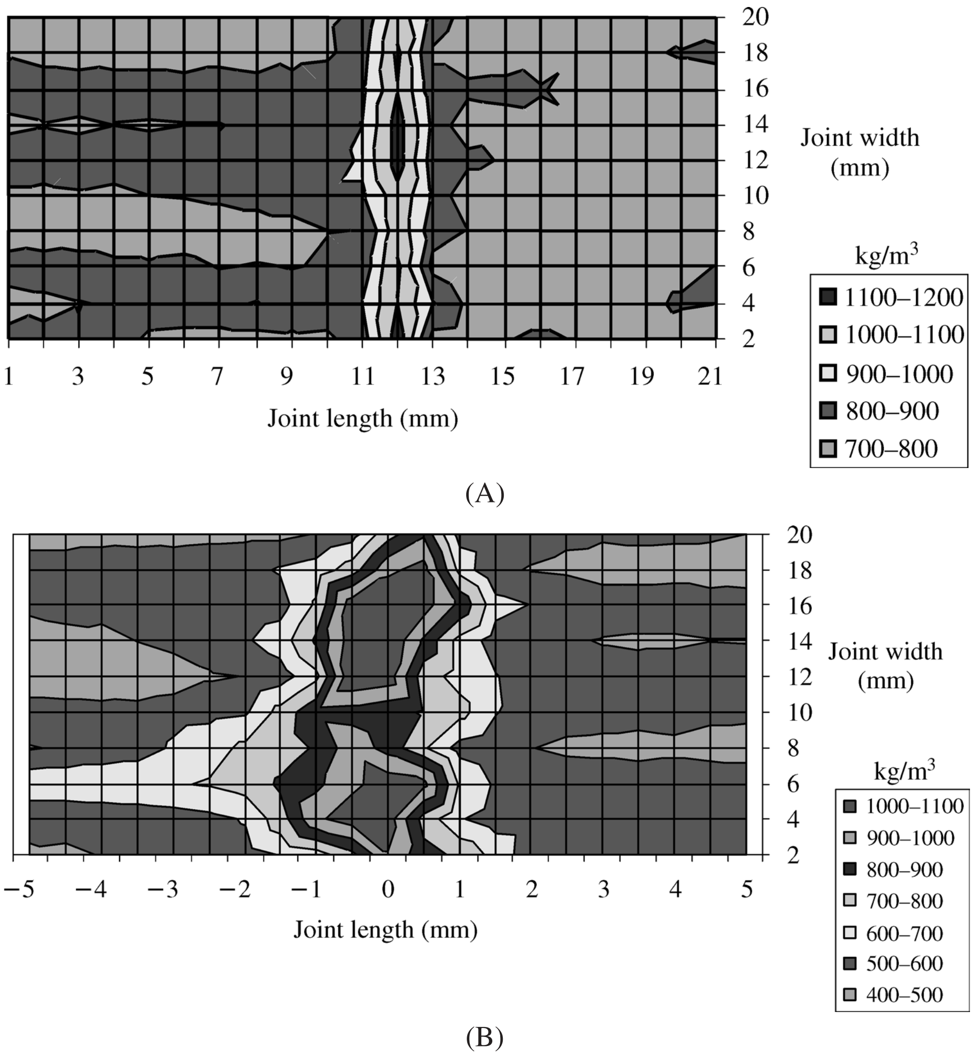


Figure 2. Maps of actual density values in kg/m^3 of (A) well-bonded vibration-welded beech wood in Fig. 1A and (B) the poorly-bonded vibration-welded Norway spruce wood in Fig. 1B.

densification process occurs and (ii) how constant it is along the sample (see Fig. 1A and 1B).

Figure 2A and 2B are top views of the wood-density variations as they are represented in Fig. 1C. The welded bond is represented in the middle of each figure. For the beech samples the increase in density is limited to one small area close to the bond (interface is about 0.6 mm thick). The average wood density of the three sections is about 760 kg/m^3 for beech while the maximum wood density attained in the bond is about 1100–1200 kg/m^3. The ratio between these two values is about 1.58 and expressed in mm of bond thickness it is about 2.63 mm.

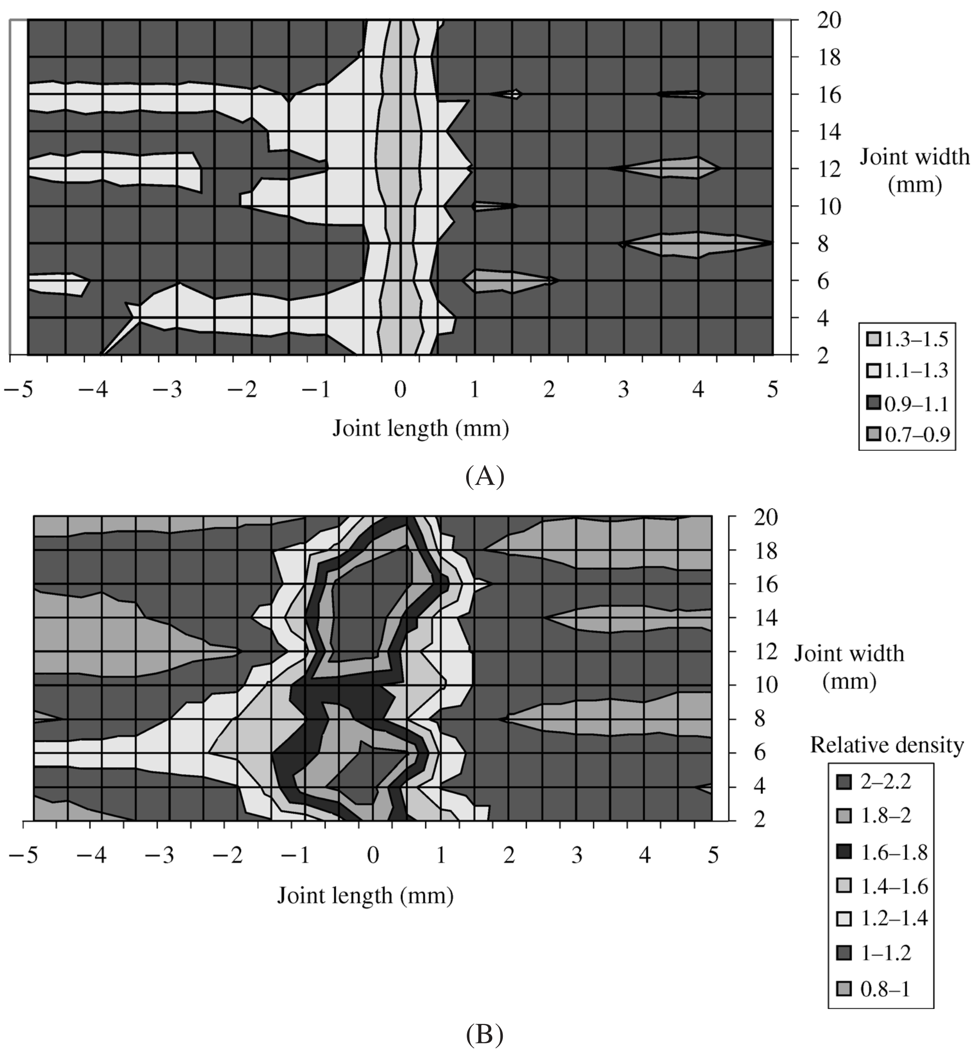


Figure 3. Relative density maps of (A) well-bonded vibration-welded beech wood in Fig. 1A and (B) poorly-bonded vibration-welded Norway spruce wood in Fig. 1B.

Figures 2B and 3B for spruce exhibit very different patterns. As in the case of beech, the welded bond is located along the vertical line at the centre of the specimen. Here, the area where wood density has increased is wider than for beech. The shape of this area looks different, mainly because of the heterogeneity of this softwood species, especially because of large variation of wood density between latewood and earlywood. This point is very clearly illustrated in the picture for spruce in Fig. 1B. In this picture one can see that the latewood parts of one sample have compressed the earlywood parts of the other sample and, as a consequence, a typical 'fingerjointing' pattern is obtained. This explains why the welded bond area has an irregular shape in terms of wood density. Even if this shape is not as well defined as for beech, which is a very homogeneous hardwood, the interface is 1.8 mm thick. If we calculate as for beech the ratio of maximum wood density to average wood density, we obtain a ratio of 2.35 (1200/510) and this ratio expressed in terms of mm of thickness of the bonded area drops to 1.30 which is about 50% lower than for beech.

X-ray-derived wood-density maps can be presented in a planar projection both as absolute density maps or as relative density maps. In Fig. 2A and 2B the absolute density maps for the well-welded beech wood joint in Fig. 1A and for the poorly welded Norway spruce joint in Fig. 1B are presented. The difference in the central zone for the absolute density maps for beech and spruce in Fig. 2A and 2B clearly shows the evenness and narrowness of the high density zone of the well-welded beech joint, and the very irregular, very broad and malformed interfacial zone of the poorly-welded spruce joint. In Fig. 2B, one can see that welding in one 'spot' has occurred also for spruce but this constitutes only approx. 20% of what should have been welded. In reality, a direct comparison of different wood species is risky when using absolute wood density maps. These maps are useful because they indicate the real densities of the various components of each joint, but this does not constitute a good basis for comparison when very different species such as a hardwood and a softwood are compared.

Relative density maps obtained by dividing density values by the mean density of the specimen are more appropriate instead for interspecies comparison. The relative density maps corresponding to the specimens shown in Fig. 2A and 2B are shown in Fig. 3A and 3B. The regularity and irregularity of the well-welded interface and poorly-welded interface, respectively, are clearly visible in these maps too. The conclusions which can be drawn are the same. The difference between the absolute and relative density maps is illustrated in Fig. 4A and 4B. Figure 4A and 4B show, respectively, the absolute and relative density profiles of welded joints of beech, spruce and oak. Figure 4A shows the real density values of the wood away from the interface and at the interface of the welded joint. Thus, oak and beech are clearly shown as higher density timbers than spruce. Figure 4B instead reports the density of the timber to a normalized value, rendering comparison easier.

An oak welded joint is shown in Fig. 5A and 5B. The interfacial bondline is well formed and regular, although not quite as sharp and narrow as that of well-

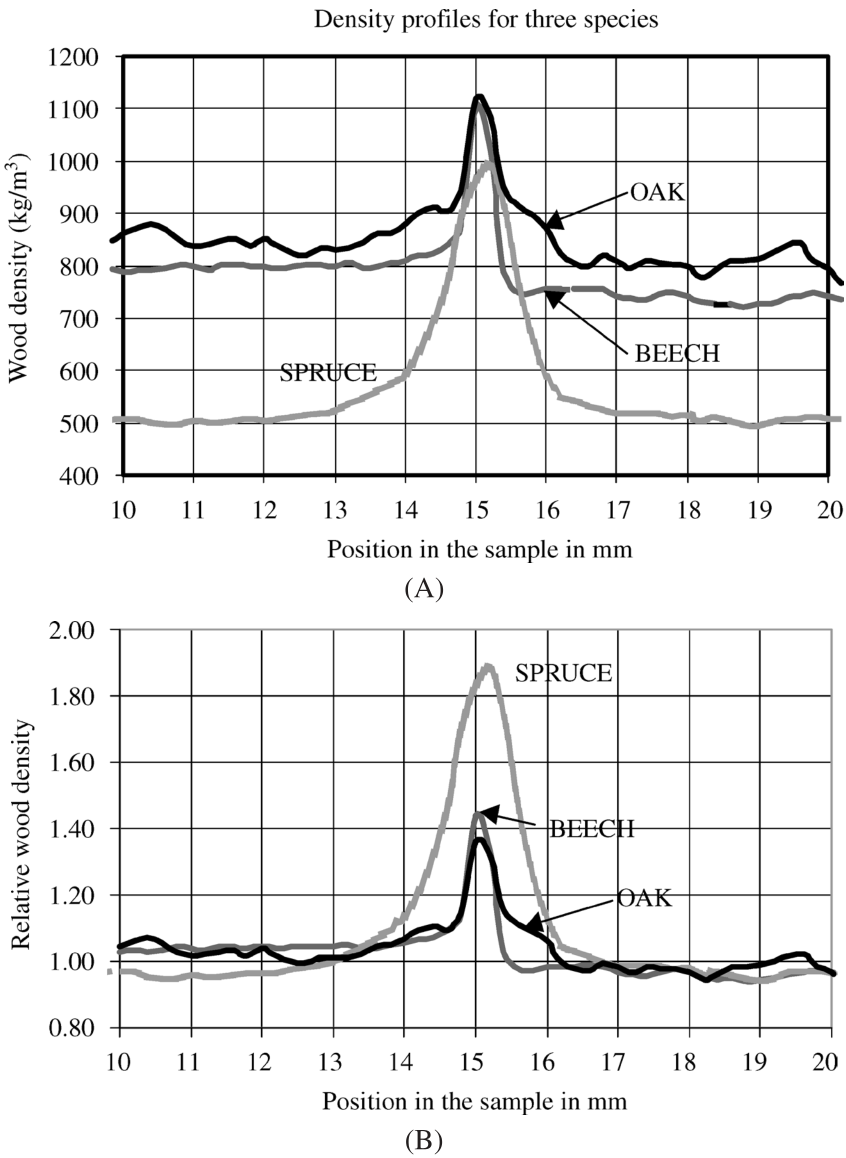


Figure 4. Density profiles for beech, oak and spruce allowing comparison of their performances. (A) Actual density profiles, (B) relative density profiles.

welded beech joints. One can observe from Table 1 and Figs 3A, 3B and 5B that the relative strengths of the welded joints are in direct relation with the evenness and narrowness of the interfacial bondline. The narrower and more even the bondline, the better the mechanical performance of the joint appears to be. Thus, in Table 1 the dry strengths of the beech, oak and spruce joints shown, respectively, in Figs 3A, 3B and 5B are reported and indicate that the narrowest and broadest bondlines correspond, respectively, to the strongest and the weakest joints. Observing Fig. 4A

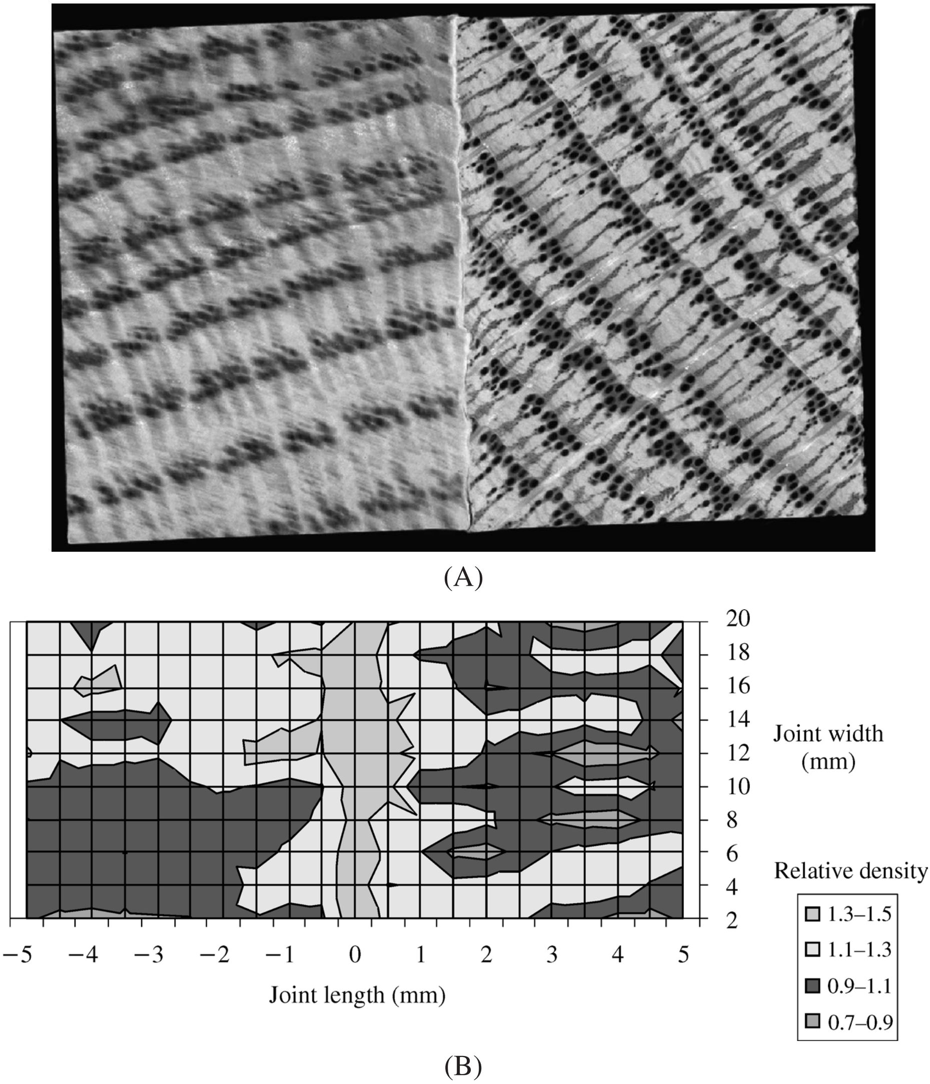


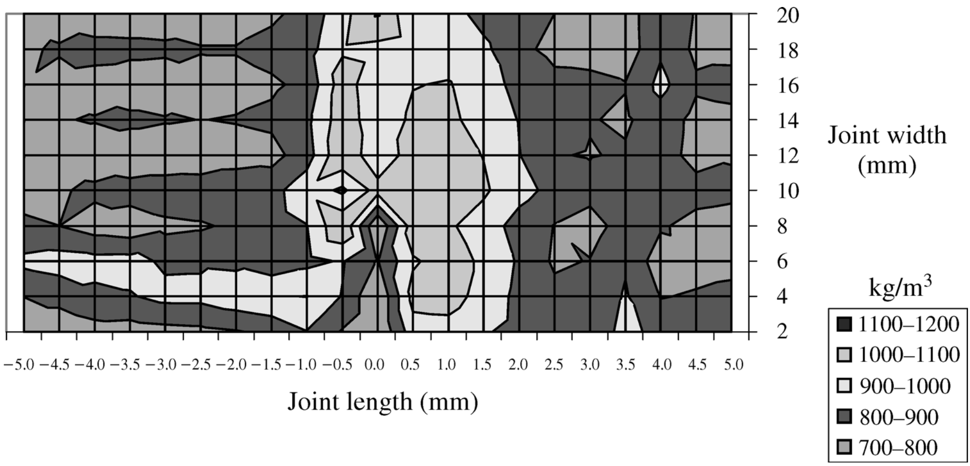
Figure 5. X-ray microdensitometry (A) photograph of well-bonded vibration-welded oak wood and (B) its relative density map.

it is noticeable that the bondline (the peak in Fig. 4A) is broadest at the base for spruce and narrowest for beech. This indicates that the bondline formed in beech by the fusion of middle lamella material is more compact and localized than in spruce.

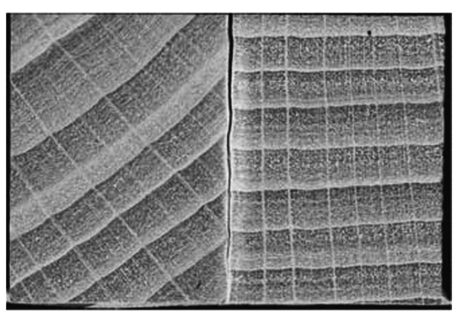
In Fig. 6A–C a specimen of a beech joint welded at one end and unwelded at the other is shown. The density maps clearly indicate where the specimen is welded and where it is not. Thus in the planar density map (Fig. 6A) one can readily see the discontinuity due to the absence of welding which can be observred in Fig. 6B. This becomes even clearer in the three-dimensional density map (Fig. 6C), where the higher density peak at the interface indicates where the specimen is welded. Where the specimen is not welded peaks indicating a density much lower than the average of the specimen can be seen.

Table 1.
Joint strengths of vibration-welded wood joints composed of different wood species

Wood species	Average joint strength (MPa)	Best result joint strength (MPa)
Beech	8.72	11.22
Oak	5.43	7.39
Spruce	4.20	4.96
Mixed Spruce/beech	4.41	6.78



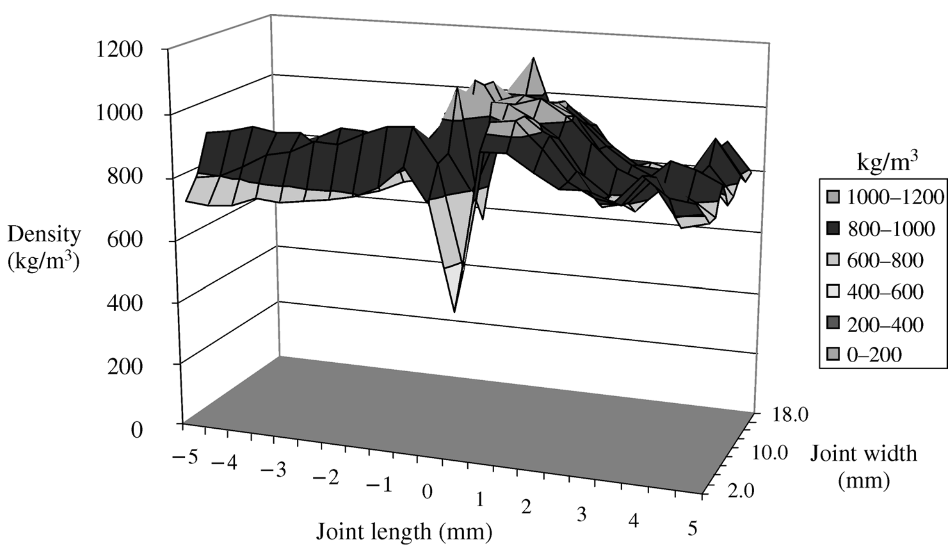
(A)



(B)

Figure 6. X-ray microdensitometry. (A) Relative density map of partially-welded beech showing the welded and unwelded parts. (B) Photograph of partially-welded beech showing joined and not joined regions of the specimen. (C) Three-dimensional wood-density map of the same joint clearly showing high-density peaks where the wood is joined and a peak of density much lower than the average wood specimen where the joining is poor or non-existent.

Mechanical welding has also been attempted between surfaces belonging to two different wood species of different characteristics, namely a hardwood (beech) and a softwood (spruce). The results obtained are shown in Fig. 7A and 7B. In Fig. 7A one can note that spruce shows the same jagged appearance of the bondline due to the collapse of the softer earlywood rings and the lack of this for the much harder latewood rings. More interesting is the appearance of the beech interface which is rather jagged (but much less than that of spruce) and is not as smooth as that in Fig. 1A characteristic of beech/beech welded joints. The indentations seen in Fig. 7A on the beech surface correspond, in general, to the pressure exercised by the higher density latewood growth rings of spruce onto the softer earlywood rings of the the other surface (beech). The density map in Fig. 7B further explains what occurs: the discontinuity at the bondline due to the considerable difference in average density of spruce and beech causes mainly to fuse the spruce earlywood part and is densified on the beech surface. It is easy to see that at the bondline the density of the spruce interface is much higher than the density in other zones of the same timber. In short, it is the lower average density spruce that mainly crushes, fuses and welds onto the much higher density beech surface. Beech does contribute more to the interface strength (Fig. 7B) as seen by the comparison of spruce-spruce, beech-spruce and beech-beech joint strengths in Table 1. However, the process is mainly dominated by what happens to the lower-density wood, as shown in Fig. 7B and Table 1. In Table 1 the strength of the mixed joint is better than in the case of spruce alone, but only approx 5% (average strength) and up to 35% (best result). The values obtained are lower than the value for beech joints only, confirming the limited contribution of beech to welding and to mixed joints strength.



(C)

Figure 6. (Continued).

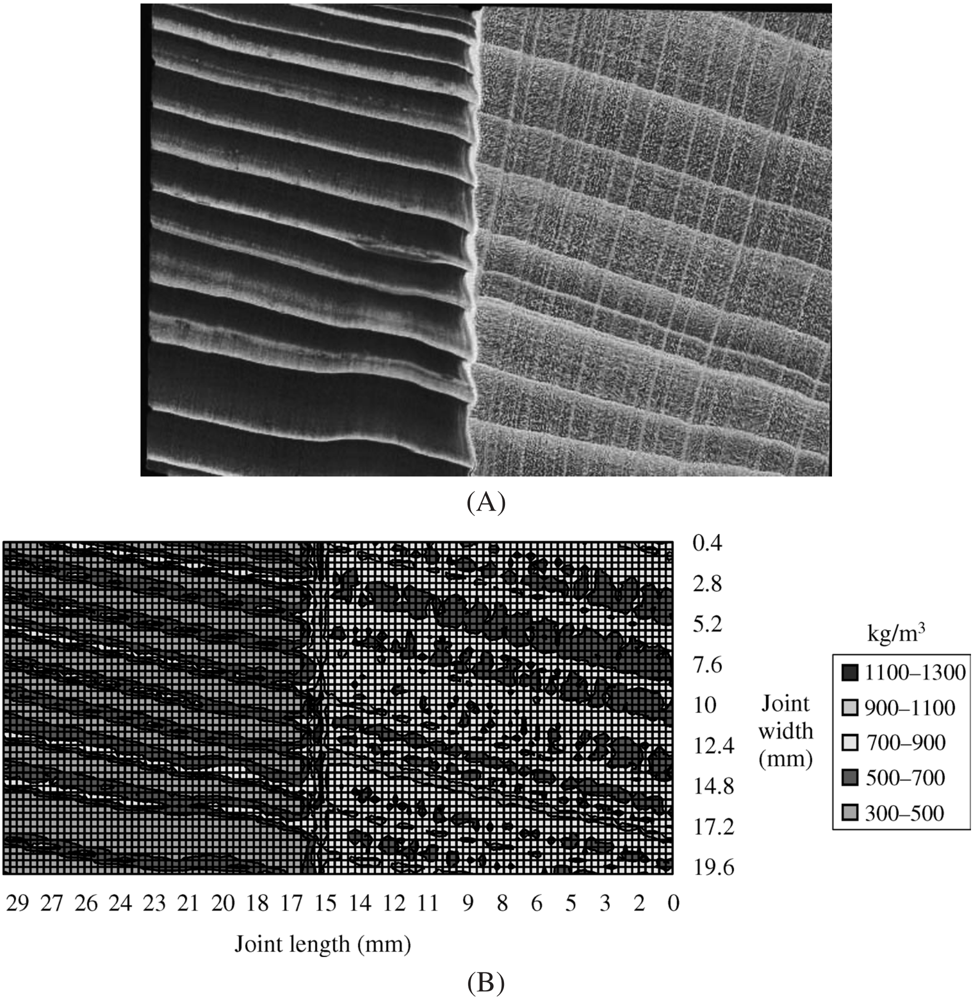


Figure 7. X-ray microdensitometry results of a welded wood joint of mixed wood species (beech and spruce). (A) Photograph of vibration-welded spruce and beech. (B) Map of actual density values in kg/m^3 of the mixed joint.

4. CONCLUSIONS

In conclusion, X-ray microdensitometry has been shown to be a valuable technique to determine the extent of wood welding. It is capable to give an indication of both the morphology of the bondline, as well as the strength of the welded joint obtained. Analysis of welded joints using three different types of wood showed that the morphological differences observed in the final joint depend quite markedly on the density and evenness of the bondline, and that these show qualitative trends similar to those observed for the strength of the welded wood joints. Spruce was shown to give inferior welding results due to its characteristic cells collapse. Spruce contribution in a mixed hardwood/softwood joint then limits the maximum joint strength achievable. The relatively poor performance of spruce is only characteristic of this species and not of softwood in general. Work in progress at present has shown that results as good as those obtained with beech wood can also be obtained with softwood other than spruce. The wood-grain orientation of the two surfaces to be bonded appears to have an influence, although not a determinant one. Thus, the present study has been limited to the average of results of a balanced mix of different grain orientations to minimize any influence this could have. A comprehensive study on the effect of grain orientation on wood welding is in progress.

REFERENCES

1. B. Gfeller, M. Zanetti, M. Properzi, A. Pizzi, F. Pichelin, M. Lehmann and L. Delmotte, *J. Adhesion Sci. Technol.* **17**, 1573–1589 (2003).
2. F. Mothe, G. Duchanois, B. Zannier and J. M. Leban, *Ann. Sci. Forest.*, **53**, 301–313 (1998).
3. V. Decoux, E. Varcin and J. M. Leban, *Ann. Forest. Sci.* (2004) (in press).
4. U. Bergsten, J. Lindberg, A. Rindby and R. Evans, *Wood Sci. Technol.* **35**, 435–452 (2001).
5. J. D. Cown and B. C. Clement, *Wood Sci. Technol.* **17**, 91–99 (1983).
6. J. R. Olson, C. J. Liu, Y. Tian and Q. Shen, *Wood Fiber Sci.* **20**, 187–196 (1988).
7. W. W. Moschler and P. M. Winistorfer, *Wood Fiber Sci.* **22**, 31–38 (1990).
8. H. Polge, *Ann. Sci. Forest.* **23**, 1–26 (1966).
9. P. Rudman, F. McKinnell and M. Higgs, *J. Inst. Wood Sci.* **24**, 37–43 (1969).
10. M. L. Parker and L. A. Jozsa, *Wood Fiber* **5**, 192–197 (1973).
11. K. Pernestål and B. Jonsson, *Wood Sci.Technol.* **30**, 91–97 (1996).