NOMINATION
LINEAR AND ROTATIONAL WOOD FRICTION WELDING WITHOUT ADSHESIVES

Mechanically-induced wood welding, wood-to-wood, without any adhesive or resin, has been shown to rapidly yield wood joints satisfying the relevant requirements for structural applications. This results in strong wood joints, without any adhesive, or any other additive, obtained very quickly, in a matter of seconds. The joints are totally environmentally friendly as they are composed exclusively of wood.

They are economically advantageous for two reasons: (1) the elimination of the adhesive in furniture and in joinery, the synthetic, polluting PVAc adhesive being the one particularly targeted for total elimination, and (2) they are obtained very quickly, developing in a matter of seconds the same mechanical resistance that joints bonded with PVAc glue develop only 24 hours after application

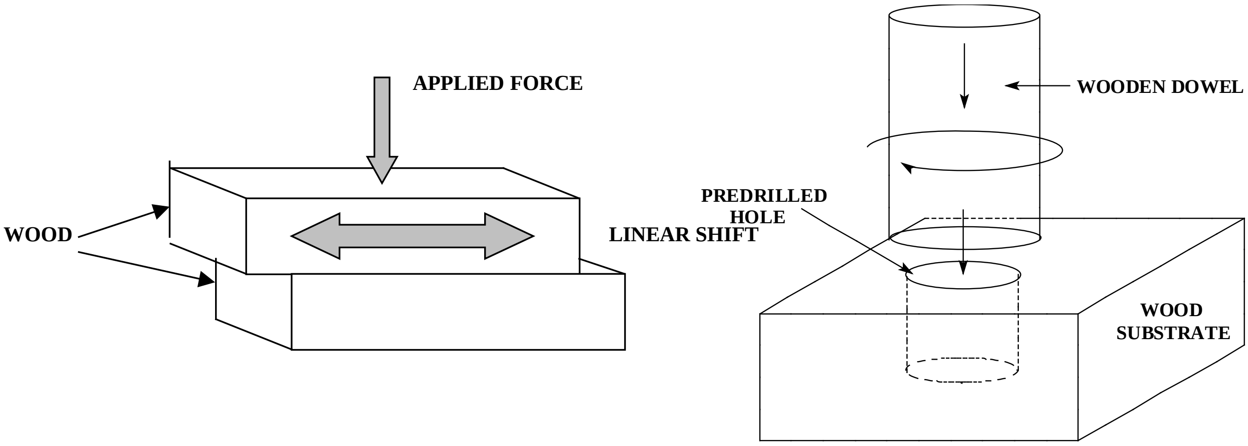
Two systems of welding wood without adhesives have been developed. (1) vibration welding used to weld two flat wood surfaces to each other, for which specialized machine already used for metal and polymer welding are used, and (2) high speed rotation welding of wood dowels into wood substrates, used to join several wood specimens with everyday, inexpensive equipment.

Both systems of wood-to-wood welding are based on the melting and flowing of the amorphous, cells-interconnecting polymer material in the structure of wood, mainly lignin, but also hemicelluloses. This is caused by the high temperature reached quicly at the interface, and at the interface only (>180°C at the interface but still 20°C at less than 1 mm from it) for an extremely short period (1 to 3 seconds). This causes partial detachment, the "ungluing" of long wood cells, wood fibres, and the formation of a fibres entanglement network in the matrix of molten material which then solidifies. Thus, a wood cells/fibres entanglement network composite having a molten lignin polymer matrix is formed. Cross-linking chemical reactions also have shown by NMR analysis to occur mainly a cross-linking reaction of lignin with carbohydrate-derived furfural produced by the heat of friction. These reactions, however, are relatively minor contributors during the very short welding period. Their contribution increases after welding has finished, explaining why, in flat wood welding, holding times up to 5 seconds, under pressure, after the end of welding contribute strongly to obtain a even better bond.

At the European level the use of this system, especially wood dowels welding, will spare considerable amounts of adhesive, in the thousands of tons, to the wood industry, in particular PVAc in the furniture and interior joinery industry. Thus the first effect is strongly economical. The second system can also be used by DIY enthusiasts, so simple it is. The second likely effect is that it would render certain sectors of the wood industry more or even totally independent of the chemical industry. The third effect would be to have wood furniture and joinery totally environmentally friendly as they would be composed exclusively of wood.

The methodology and technology used and the innovative solution:Wood welding without adhesives

Specimens composed of two pieces of beech wood (*Fagus sylvatica*), each of dimensions 150x20x15 mm, were welded together to form a bonded joint of 150x20x30 mm dimensions by a vibrational movement of one wood surface against another at a frequency of 100 Hz. The results were then extended and proven with wood planks of dimension 600x80x20 mm to yield welded joints of 600x80x40 mm dimensions. The parameters which yielded the best results were: welding time = 3s; the contact holding time (H.T.) mantained after the welding vibration had stopped = 5 seconds; the welding pressure = 2 MPa; the holding pressure after the welding had stopped = 2.7 MPa); the amplitude (A.) of vibration = 3 mm). Equally, beech dowels of 10 mm diameter were intoduced at 1200 rpm within a hole of 8 mm of the same beech wood. When fusion and bonding were achieved, the process was stopped. The clamping pressure was then briefly maintained for both processes until the solidification of the bond. 10 replicas of each specimen were tested in tension. The movements used were as follows:



Scanning electron microscopy (SEM) micrographs of the surfaces of the joints opened by mechanical testing were obtained after metallizing with gold-palladium.

Three sections from each of these samples were tested by X-ray microdensitometry.

The average wood welding tensile strengths obtained under the conditions outlined were between **10 and 11 MPa** and were obtained at 3s welding time and 5s holding time. The average results satisfy the requirements of the EN 205-D1 specification (European Norm EN-205D1, 1992). Increasing welding time decreased joint tensile strength. Welding pressures higher than 2 MPa yielded worse results due to incipient bond degradation. The temperature of just the bondline reaches 170°C or higher during welding. This temperature is much higher than T_g of lignin and hemicelluloses, above which materials are known to flow. Melting of some of the major structural, polymeric wood constituents occurs as observed by SEM (Fig. 1). In Fig. 1 fibres, long wood cells (tracheids), immersed in a mass of molten polymer can be observed . The cells do not appear to be greatly damaged, hence melting has occurred mainly in the intercellular connecting tissue or *middle lamella.* Wood *middle lamella* is particularly rich in lignin, more than any other anatomical feature of wood. The welded bondline is then composed of a mass of entangled long wood cells immersed in a matrix of amorphous, fused intercellular material, mostly lignin but also including some hemicelluloses. C-13 NMR spectra indicated that chemical cross-linking reaction of lignin and of carbohydrates-derived furans also occurred. These contributed to the mechanical resistance but to a minor extent. Constant heating rate thermomechanical analysis of welded bondline joints yield a marked increase of the modulus of elasticity (MOE) of the joint at increasing temperatures. This further contribution to the joint strength comes to bear only after welding has finished. This might be why the longest holding time under pressure after the end of welding contributes markedly to the formation of a good bond.

Figures 2 and 3 show the density maps by X-ray microdensitometry of the linear and rotational friction-welded joints. In Fig. 2 the welding line is in the middle of the figure. The increase in density is limited to one small area close to the bond, about 0.6 mm of the joint's width (Fig. 2).

The average wood density of the beech sections is about 760 kg/m^3 while the maximum wood density in the bond is much higher at about 1100-1200 kg/m^3 (Fig. 2). Figs. 3 and 4 shows the X-ray densitometry derived density maps of the rotational friction-welded dowel joint. It shows that approximately 60% of the joint surfaces have been welded, although densification has occurred even where welding has not. Allignement is then an important aspect of rotational welding of ribbed dowels within a timber surface. Dowels welding without adhesives and using simple equipment has given dowel withdrawal strengths comparable to those of dowels bonded with PVAc glues. Thus optimization of the ribbed **dowel welding** has given **average** tensile strength of the **dowel joint of 3300 N/mm^2 after 2 seconds** dowel welding, which compare with results of **3300-3400 N/mm^2 obtained with PVAc after 24 hours gluing**.

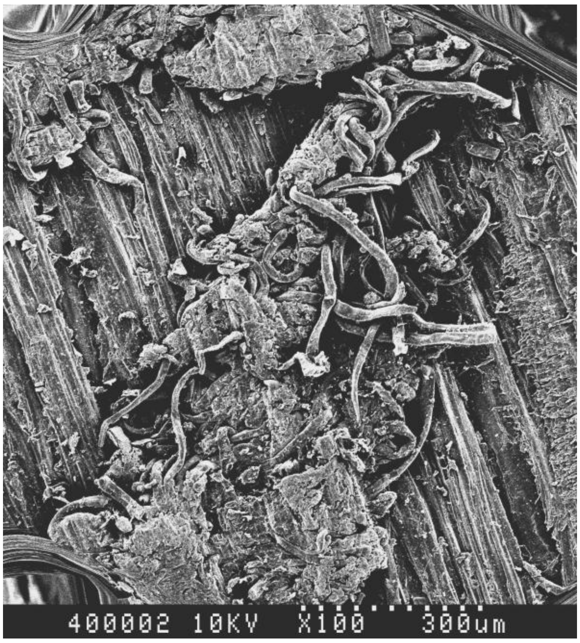
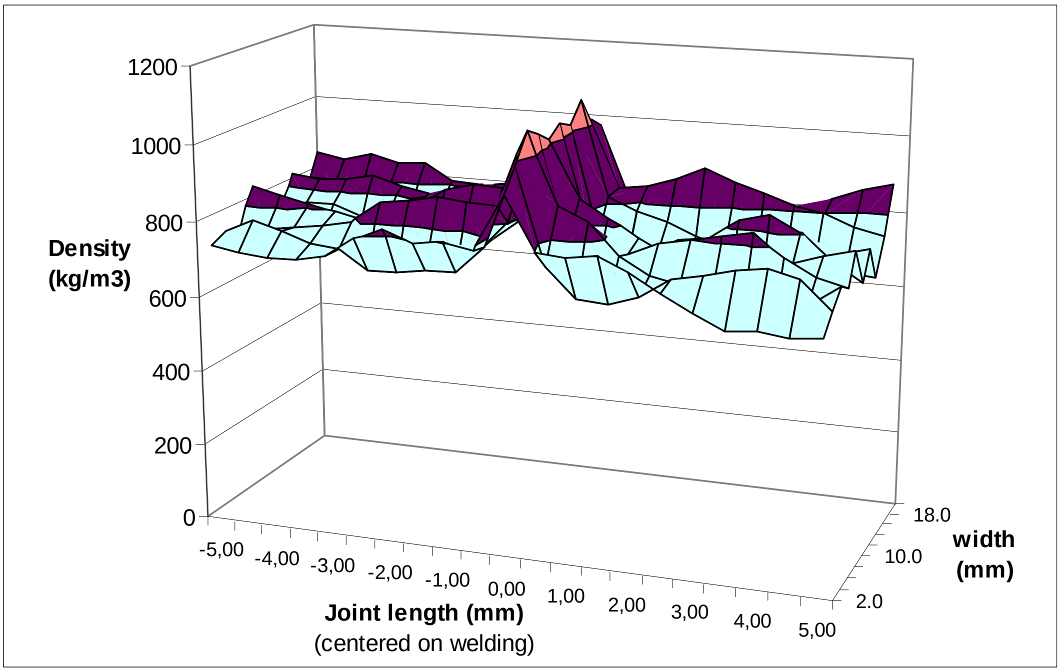


FIG. 1. Scanning electron microscopy image of entangled beech wood fibers in a matrix of melted intercellular material obtained by linear flat welding of wood.

FIG. 2. X-ray microdensitometry map of actual density values in kg/m^3 of well bonded linear vibration welded beech wood. Note the considerable increase in density of the bondline.



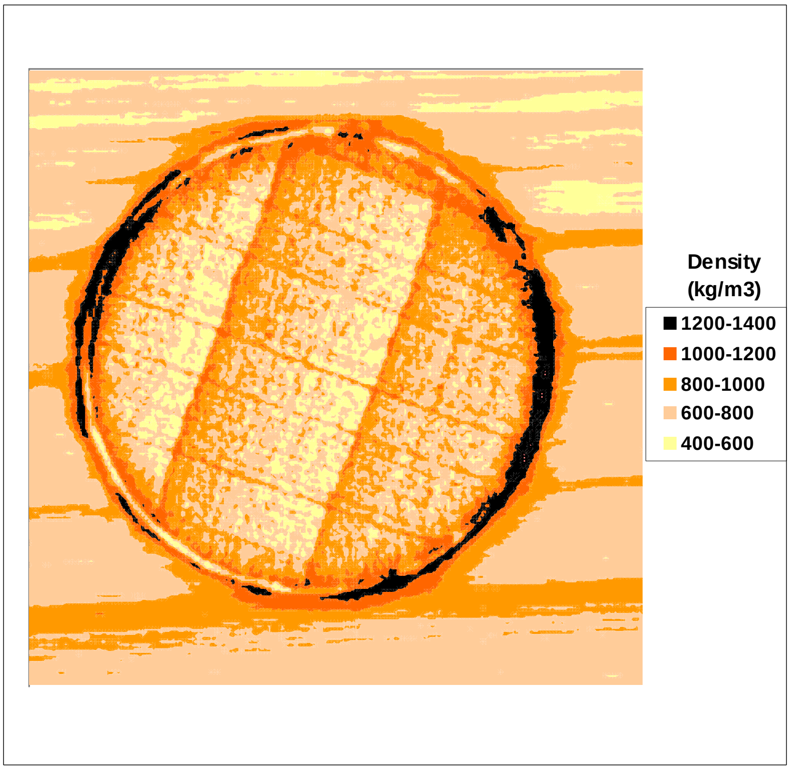


FIG. 3. X-ray microdensitometry map of actual density values in kg/m^3 of well-bonded rotationally welded beech wood dowel. Normal section.

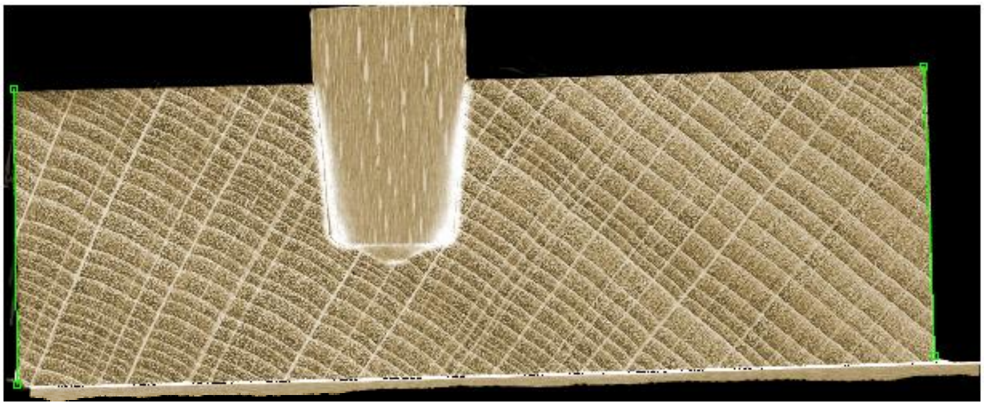


FIG. 4. X-ray microdensitometry photograph of side section of a well-bonded rotationally-welded beech wood dowel.

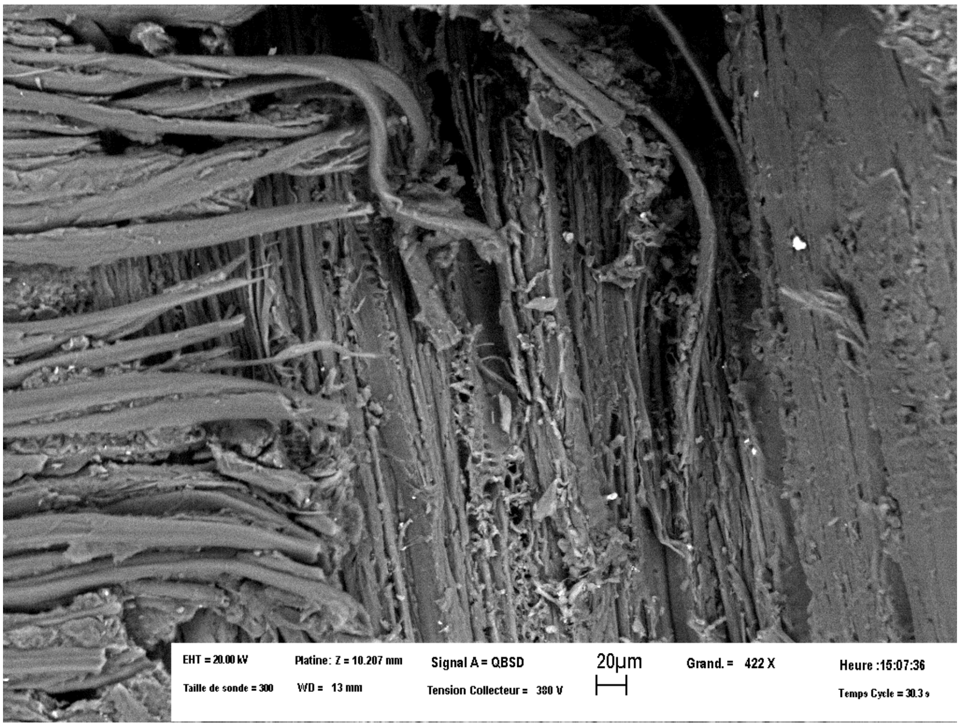


FIG. 5. Scanning electron microscopy photograph of the surface of a tensile-tested dowel after welding. Note the vertical direction of the dowel fibres, the orizontal direction of the substrate hole fibres bonded by fused intervcellular material the ones to the others.

Innovative character of the submitted work

Solid wood welding just by fusion of the wood, as in metal welding, did not exist before our work. For bonding furniture and interior joinery only synthetic, oil-derived adhesives are used, such as PVAc and formaldehyde-based adhesives. With this process adhesives are not needed anymore as only natural wood is used. A completely environment-friendly process and product.

The innovative character in developing mechanically-induced wood bonding technology, without the use of adhesives, suitable for application in the European market is multifold:

(a)- Never before elimination of the adhesive from interior wood joints has been achieved. Thus, for the first time has been achieved total elimination of potentially toxic products, the synthetic adhesives, used in furniture and interior joinery, such as formaldehyde-based adhesives and vinylic and acrylic resins the residual monomers of which are always present, volatile and toxic. For such a reason a purely mechanical process is much more acceptable from an environmental protection point of view than the synthetic polluting materials which dominate this market at present.

(b)- Never before the bonding rate has been so fast. The bonding rate of mechanically-induced welding is much faster than that of any synthetic adhesive used to-day in bulk amounts in the furniture and interior joinery industry. This is an important consideration which translates in faster production times with consequent financial advantages.

(c)- Never before mechanical joints with thin, molecular level bondlines have been achieved with characteristics which are comparable and in certain applications even superior to wood joints bonded with currently-used adhesives based on oil-derived synthetic polymers.

(d)- Never before it has been achieved the financial advantages of eliminating the expenditure of buying adhesives or metallic joining pieces, and these products so swiftly and elegantly eliminated..

(e)- Never before a process (the dowel fusion one) to bond wood dowels has been developed that is so easy to implement to be affordable even with to-day's existing DIY tools even for small backyard workshops and for the DIY market.

(f)- Never before a process (the dowel fusion one) to bond wood dowels has been capable of achieving such heights of strength (about 20 times higher what achieved with hammer-introduced dowels).

Future prospects

The expected impact and future prospects of the technologies developed are as follows:

1.- The industrial introduction in Europe of totally environmentally-friendly, non-toxic solid wood bonding process, without neither VOC (volatile organic compounds) emission nor any formaldehyde and residual vynyl monomers emission. This is real ecological use of renewable resources.

2.- The industrial introduction in Europe of a revolutionary process to bond wood not needing any synthetic, oil-derived adhesive.

3.- The industrial introduction in Europe of a cheaper wood bonding process in which the cost of the adhesives used to-day is saved. Just for the purposes envisaged the amount of PVAc polymer used in Europe to-day is well in excess of 100 000 tons per year, at 2000 euros per ton. The economic advantages for the timber industry are then quite evident. It is aspected that a good percentage of this market could switch to the new process.

4.- The industrial introduction in Europe of a process (the dowel fusion one) to bond wood dowels that is so easy to implement to be affordable even with to-day's existing DIY equipment even for small backyard workshops and for the DIY market.

On the technical side further development is ongoing with the extension of this work to structural applications in wood-based civil engineering. On this from major contributions have been made by two of the candidates (Ganne-Chedeville and Mansouri) by fracture mechanics studies and the development of the terchnology of waterproofed, totally natural wood welded joints (Mansouri) that has openbed the market to civil engineering structures. Further optimization of the technology for a variety of different timber-joining cases was done by one of the four proposed candidates (Segovia-Brandt). Considerable interest is present in PME for these process, in particular for the dowel welding one as for this process machinery already existing in current timber companies can be used for the purpose without any further capital expenses.

While considerable progress has been made in the very recent field of wood welding 4 names of young scientists of the newer generation stand out as having made recently important contributions to this field.

Namely:

1.Dr Christelle Ganne-Chedeville of the University of Applied Science Fachhochschule, Biel, Switzerland, particularly for her interesting work on fracture mechanics

2. Dr Hamid Reza Mansouri, formerly of the ENSTIB, University Henri Poincaré-Nancy 1 in France and now senior lecturer at the Dept. of Wood Science at the University of Zabol , Zabol, Iran. In particular for his work on butt jointing of australian eucalyptuses and the development of a system of waterproof wood weld opening the exterior structural market to

3.Dr Mojgan Vaziri, of the Technical University of Lulea, Skelleftea, Sweden, for the study of the movement through the welded interface and its and resistance to water by NMR imaging techniques.

4. Dr Cesar Hernan Segovia-Brandt, of the ENSTIB, University Henri Poincaré-Nancy 1, for the development and optimisation of all the different furniture joints that can be odone by wood welding.

List of relevant publications of the 4 nominees on international refereed journals on wood welding

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