Holz als Roh- und Werkstoff (2005) 63: 251–255
DOI 10.1007/s00107-004-0569-8

ORIGINALARBEITEN/ORIGINALS

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Surface finishes by mechanically induced wood surface fusion

Published online: 10 May 2005

Abstract Mechanically induced vibration wood fusion welding techniques can also be used to obtain wood surface finishes of increased surface hardness and performance in presence of polymerizing unsaturated oils such as sunflower oil, or other polymerizing finishes. Wood surface hardness values more than double than those for the untreated control timber can be obtained by this method. This result is obtained due to two effects induced by the sharp increase in temperature induced by the mechanical welding vibration (i) the polymerization to a hardened network of the unsaturated oil and (ii) the densification proven to occur in the surface layer of the timber during mechanically-induced vibration-welding. The first of these effects predominates at shorter welding times while at slightly longer welding times both effects occur with the second one progressively becoming the bigger contributor. In the latter case the some μm thin densified surface is a surface composite formed by the networked unsaturated oil permeating the wood fibre/fused lignin composite.

Oberflächenvergütung mittels mechanisch induzierter Holzoberflächenverschmelzung

Zusammenfassung Mechanisch induzierte Vibrations-Schweiß-Techniken bei Holz können ebenso angewandt werden, um Holzdeckschichten von erhöhter Härte und Widerstandsfähigkeit in Gegenwart von polymeren ungesättigten Ölen, wie z.B. Sonnenblumenöl, oder anderen polymerisierenden Beschichtungen zu erhalten. Auf diese Weise lassen sich mehr als doppelt so hohe Härtewerte für Oberflächenschichten von Holz erreichen, als für Kontrollproben von unbehandeltem Holz. Dieses Ergebnis ist die Folge von zwei Einflüssen, welche durch den steilen Temperaturanstieg der mechanischen Schweißvibration hervorgerufen werden (i) die Einwirkung der Polymerisierung auf ein gehärtetes Netzwerk des ungesättigten Öls, und (ii) durch die Verdichtung, welche nachweislich in Deckschichten von Schnittholz während des mechanisch induzierten Vibrationsschweißvorgangs auftritt. Erster überwiegt bei kurzen Schweißzeiten, während bei etwas längeren Schweißzeiten beide Einflüsse auftreten, wobei der zweite sich nach und nach zum stärkeren Faktor entwickelt. In letzterem Fall stellt die einige μm dünne, verdichtete Oberfläche einen Oberflächenverbund dar, welcher dadurch entsteht, dass das vernetzte ungesättigte Öl die faserverschmolzene Ligninmasse durchdringt.

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1 Introduction

Mechanically-induced friction welding techniques which are widely used in the plastic and car industries have recently been applied also to joining wood, without the use of any adhesive (Gfeller et al. 2003, 2004). These 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 immersed in a matrix of melted wood intercellular material, such as lignin (Gfeller et al. 2003, 2004). 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 (Gfeller et al. 2003, 2004). 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 proper but acquire

more importance after the welding period proper (Gfeller et al. 2003, 2004).

Wood density is often one good estimator of other physical and mechanical wood properties. X-ray microdensitometry is a technique recently used to investigate solid wood density distribution (Decoux et al. 2004; Mothe et al. 1998), adapted and applied for the quantitative analysis of the intra ring wood density variations (Decoux et al. 2004; Mothe et al. 1998). It indicates the distribution of any densification, special low and high features, such as wood growth rings, compression and tension wood in solid wood samples (Decoux et al. 2004; Mothe et al. 1998). Recent developments have been carried out for (i) the automatic treatment of the X-ray pictures (Decoux et al. 2004; Mothe et al. 1998) as well as for the comparison between the wood density values and the anatomical variations of the cell sizes (Decoux et al. 2004). The application of X-ray microdensitometry to wood-welded surfaces has indicated a considerable and interface localized increase in the density at the interface of the two welded wood surfaces (Leban et al. 2003).

This indicated that if an autopolymerizable material is added as a lubricant to a wood surface, frictionally induced wood welding can be avoided for a certain length of time while still obtaining densification by wood fusion. The combination of an autopolymerizable finish, especially if this is a non-toxic natural material and microndeep wood surface densification by fusion could then be used to improve smoothness and mechanical resistance of a wood surface, and thus work as a wood surface finish.

2 Experimental

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

2.1 Preparation of surfaces by mechanically-induced wood fusion and their testing

Specimens composed of two pieces of beech (*Fagus silvatica*) cut in the tangential direction, each of dimensions 150×20×15 mm, were friction treated by a vibrational movement of one wood surface against another at a frequency of 100 Hz, as for welding them together but in presence of sunflower oil on the two surfaces to stop actual bonding. When some fusion was achieved, at different treatment times the vibration process was stopped. The clamping pressure was then briefly maintained until the solidification of the surface. The welded samples were conditioned for 1 week in an environmental chamber (20°C and 65% RH) before testing.

The parameters which were used were adapted from those optimized in the preceding study (Gfeller et al. 2003), with some variations, one being the presence on the surface of an unsaturated oil, sunflower oil, and the other being the mechanical vibration time used: namely welding times (W.T.) of 3, 4, 6 and 9 s were used. The other conditions used were as described before (Gfeller et al. 2003): a contact holding time (H.T.) maintained after the welding vibration had stopped for 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 the 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%. An untreated control sample to which was added a one coat polyurethane surface finish was used as a control.

These samples were used to determine the Brinell Hardness. The Brinell hardness test method consists of indenting the test material with a 10 mm diameter hardened steel sphere subjected to a load of 500 N. The diameter of the indentation left in the test material is measured. The Brinell hardness number (BHN) is calculated by dividing the load applied by the surface area of the indentation according to the expression

$$\mathrm{BHN} = \frac{F}{\left(\pi/2D\left(\sqrt{D^2 - d^2}\right)\right)}$$

where D is the diameter of the striking steel ball (= 10 mm), d is the diameter of the indentation left on the surface to be tested, and F is the force exercised (here 10 d N) according to NF B51-126 (1976).

From these samples sections of 1.88 ± 1 mm thickness, of weight 0.79–0.85 g for beech and density of, respectively, 760–783 kg/m^3 were obtained and tested by X-ray microdensitometry.

2.2 X-ray microdensitometry

The X-ray microdensitometry equipment used consists of an X-ray tube producing "soft rays" (low energy level) with long wave characteristics emitted through a beryllium window. This device is used to produce an X-ray negative photograph of approximately 2 mm thick samples, conditioned at 12% moisture content, at a distance of 2.5 m from the tube. This distance is important to minimize blurring of the image on the film frame (18×24 cm) which is generally used. The usual exposure conditions are: 4 h, 7.5 kW and 12 mA. Two calibration samples are placed on each negative photograph in order to permit the conversion of the levels of grey in wood density values. The specimens were tested in this manner on equipment composed of an electric generator INEL XRG3000, a X-ray tube SIEMENS, FK60-04 Mo, 60 kV-2.0 kW, and Negative film KODAK Industrex type M100.

2.3 Measurement of the water wetting angle

Wettability of a surface by a liquid can be measured by the wetting angle formed by the liquid on the solid substrate surface. A liquid wetting, ideally a solid surface, spreads on this surface up to a state of monomolecular film with a contact angle of 0° or with a very small contact angle. In case of an ideal non-wetting liquid or of an ideal totally liquid repellent substrate surface the contact angle would be of 180°. Thus the wetting angle of water on a surface indicates the potential water repellancy and water resistance of the substrate surface. The wetting angle is not independent of time, and its variation with time is also an important measure of the wetting stability of the resin. Triplicate series of measurements of the water wetting angle on the surfaces of the oil-treated wood fused surfaces, of an untreated wood control and of a one layer polyurethane varnish-treated but not fused control were made with each measurement at 30 s interval for a period of 15 min, using a Kruss G40 computerized contact angle machine by initially placing an identical size water drop on the treated wood surface by means of the machine microsyringe.

3 Results and discussion

The Brinell hardness increase as a function of welding time is shown in Fig. 1. This indicates that a harder surface has been produced when applying an unsaturated oil coupled with wood surface fusion due to the heat generated by the vibrational-welding treatment. Two factors are likely to contribute to the improvement in wood surface hardness: (i) the polymerization to a hardened network of the unsaturated oil (Pizzi 1990, 1993), and (ii) the densification proven to occur in the surface layer of the timber during mechanically-induced vibration-welding (Gfeller et al. 2003, 2004; Leban et al. 2003). The considerable increase in temperature during vibration welding (Gfeller et al. 2003, 2004) and the temperature dependence of unsaturated oils radical polymerization (Pizzi 1990, 1993) indicate that the first of these effects definitely occurs. No oil leaches after the treatment under any of the conditions which have been tried. That the oil has polymerized is also shown by the smoothness of the observed surface and by the scanning electron microscopy micrograph shown in Fig. 2. In Fig. 2 the shiny appearance of the cured oil network is clearly visible, superimposed and permeating the wood anatomical structure confirming that the unsaturated oil has indeed networked. However, the tridimensional cured networks formed by these oils while contributing to the smoothness of the finish never have a density of cross-linking sufficient to justify the marked increase in the wood surface Brinell hardness number observed in Fig. 1. Unsaturated oil networks have low cross-linking density and are not very hard, and perhaps could just justify the first increase of BHN from 3.2 of the control to 4.1 of the 3 s treatment. It can be observed that the slope of the curve starting from the 4 s treatment changes indicating that the second effect is the one that most contributes to the further increase in surface hardness. The presence of the oil coating the wood structure as shown in Fig. 2 does contribute to the water repellancy of the surface.

To check if it is indeed the second effect that contributes to the marked increase in surface hardness, X-ray microdensitometry of sections of the treated surfaces were performed. Figure 3 shows the section of one of the 9 s treatment specimens. Along the whole length of the left-hand side edge of the specimen one can notice a superficial thin layer of much increased density, caused by wood fusion due to the high temperature induced by vibration welding (Gfeller et al. 2003, 2004). This thin layer of increased density starts to appear, at first

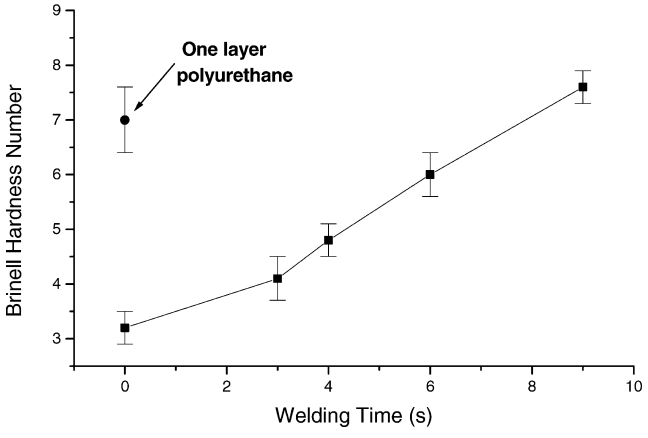

Fig. 1 Variation of the BHN of beech wood surface as a function of mechanical friction time with confidence intervals
Abb. 1 Variation der Brinell-Härte (HB) einer Buchenholzoberfläche als Funktion mechanischer Reibungszeit mit Vertrauensintervallen

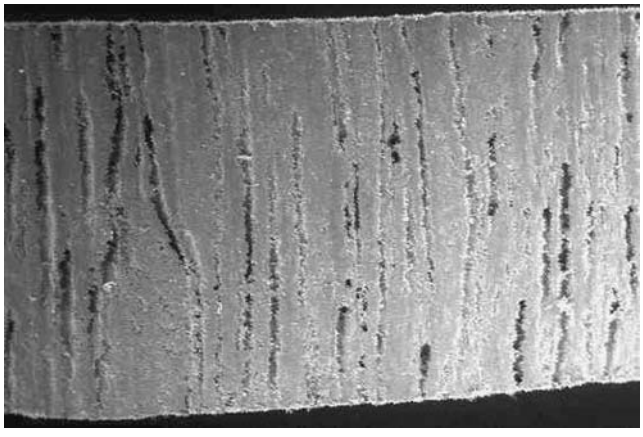

Fig. 2 Scanning electron microscope detail of a beech surface treated in presence of sunflower oil for 3 s friction time
Abb. 2 REM-Aufnahme: Ausschnitt einer Buchenholzoberfläche welche in Gegenwart von Sonnenblumenöl mit 3 Sekunden Reibungszeit behandelt wurde

inconsistently, at 4 s welding and becomes progressively more noticeable and consistently present as one passes on to 6 and 9 s welding. It does not appear to occur at 3 s welding, confirming the results of the change in slope in the dependance of the Brinell hardness noticed in Fig. 1. The thin, high density surface layer so formed has a thickness variable between 10 and 400 μm, the average range being of 300–380 μm, and a density of between 800 and 1200 g/cm^3 as identified by the scale within Fig. 3. This high density layer is a major contributor to the improved wear resistance (Fig. 1) and water repellancy (Fig. 4) of the wood surface so treated.

The permanence of a water barrier due to the 10–400 μm thin (in average 300–380 μm) densified surface composite formed by the networked unsaturated oil permeating the wood fibre–fused lignin composite was checked by determining water's wetting angle on the treated and untreated surface, and its variation as a function of time. The results obtained are shown in Fig. 4, and indicate that the densified surface composite also forms a good water barrier. In Fig. 4 the control wetting angle curve of untreated beech wood is compared to the equivalent curves for the 3 s fusion treatment and the 6 s fusion treatment in presence of an unsaturated oil, thus treatments yields at different slopes in Fig. 1. Both the 3 s and 6 s curves show a better water barrier due to the presence of the hardened, networked unsaturated oil in the timber surface. However, there is not much difference between the 3 s and 6 s treatment curves indicating that it is the presence of the polymerized unsaturated oil affording water repellance and not the additional densification caused by the mechanically induced wood fusion. Thus, wood fusion contributes to wear resistance of the surface due to materials densification, while the polymerized oil network contributes to improve water repellancy of the surface.

In conclusion the results outlined above indicate that wood surfaces wear and water resistance can be upgraded by a short vibrational welding technique in presence of a self-polymerizing compound, such as the oil used in this case.

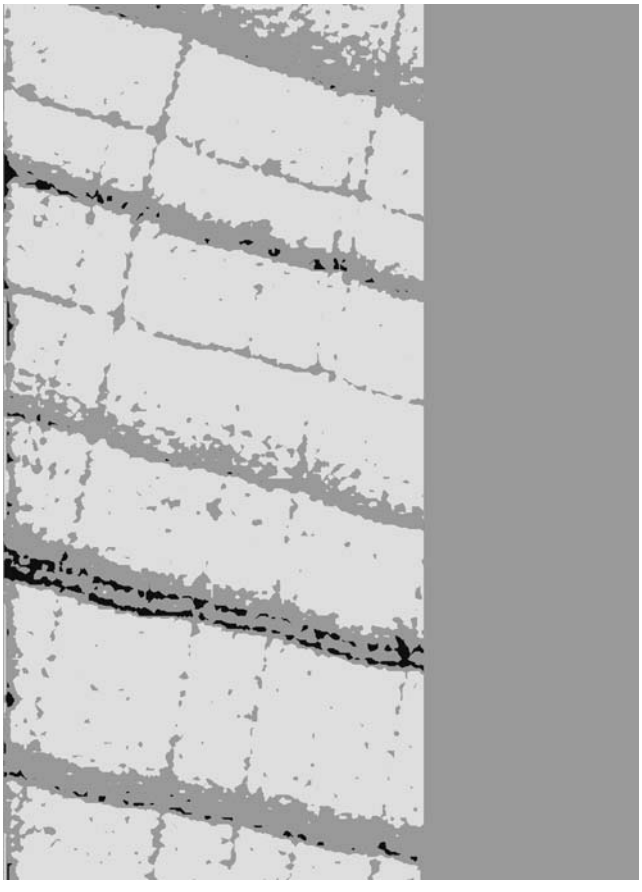

Fig. 3 X-ray microdensitometry density map of section of beech wood specimen treated in presence of sunflower oil for 9 s friction time. Note thin layer of higher density on the treated surface (*the one on the left hand side*)
Abb. 3 Übersicht der mit dem Röntgenmikrodensitometer aufgenommenen Dichteverteilung eines Buchenholzschnittes. Das Holz war in Gegenwart von Sonnenblumenöl mit 9 Sekunden Reibungszeit behandlet worden. Bemerkenswert ist die dünne Schicht von höherer Dichte auf dem behandleten Teil der Oberfläche (linke Seite)

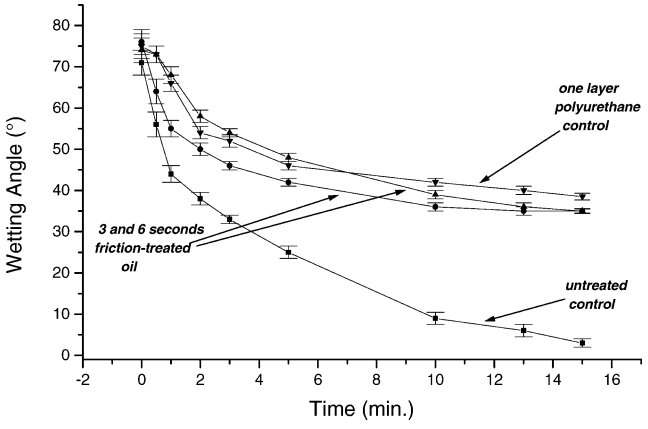

Fig. 4 Variation of water wetting angle as a function of time for an untreated beech wood surface (*filled square*), for a beech surface treated in presence of sunflower oil for 3 s friction time (*filled circle*), for a beech surface treated in presence of sunflower oil for 6 s friction time (*filled triangle*), and for untreated wood to which has been applied one layer of a polyurethane surface finish (*filled inverted triangle*)
Abb. 4 Variation des Benetzungswinkels als Funktion der Zeit für unbehandelte Buchenholzoberfläche (*filled square*), für Buchenholzoberfläche, behandelt mit 3 Sekunden Reibungszeit in Gegenwart von Sonnenblumenöl (*filled circle*), für eine Buchenholzoberfläche behandelt mit 6 Sekunden Reibungszeit in Gegenwart von Sonnenblumenöl (*filled triangle*), und für unbehandeltes Holz, auf welches eine Polyurethandeckschicht aufgetragen wurde (*filled inverted triangle*)

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