The Bonding of Modified Wood using Wood Welding Techniques

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Keywords: Dowels, modified wood, soak testing, wood welding

ABSTRACT

The development of wood welding represents one of the more innovative aspects of wood adhesion in recent years. The process, involving the thermal softening and flow of wood components, in order to allow cross-linking and subsequent hardening / polymerisation, results in bonding of adequate strength compared to conventional adhesion systems. There has been considerable activity in France and Switzerland developing the process concepts, and gathering test results. One area of particular interest has been on the welding of modified timbers. This is an area of limited study to date, but could provide benefits to welding technologies, since the wood weld may prove less susceptible to moisture uptake and subsequent bond failure. This paper will consider a series of tests undertaken with Sitka spruce, whereby acetylated, furfurylated and heat treated samples were compared to unmodified material. Samples were bonded *via* the frictional bonding of dowels, linear welding and conventional glue bonding. This paper will present results from these tests, as well as discussing future studies planned.

INTRODUCTION

Whilst frictional welding of metals and thermoplastics have been demonstrated over the past 50 years, the application of the process to wood was not shown until 1996, when Suthoff *et al.* patented work carried out in Germany. This and a subsequent patent (Suthoff and Kutzer 1997) firstly demonstrated that wood could be welded by means of either an oscillating or linear frictional action, then suggested the possibility of joining pieces of timber with a dowel. The concept of work under an inert atmosphere was also put forward. Whilst the concept of inert atmospheres had been considered for metals and thermoplastics, it had been shown that atmospheric conditions played little effect on the welding procedure. However, given the potential of charring and combustion of wood, the concept of inert atmospheres has greater credence.

The majority of recent work has been based in Switzerland and France, with work at affiliated groups across Europe. The majority of the material that has been considered to date has been Norway spruce (*Picea abies*) and beech (*Fagus sylvatica*), representing chief commercial species in Switzerland. However, to date, most work has been carried out on small scale samples (typically 150x20x15 mm). Good bonding has been noted, with tensile strengths between 8-10 MPa for beech and 2-5 MPa for spruce noted, though welded material was found to be moisture sensitive, such that their possible use has been restricted to indoor applications. Of more interest has been the temperatures achieved at the weld interface (up to 210 ^{o}C), whilst ambient temperatures were monitored 1mm away from the interface.

Rotational and linear bonding techniques have been demonstrated to date, with emphasis on the ability to create high-quality, environmentally friendly wooden joints free of adhesive or other chemical additives. The bonded regions have been shown to have higher density (Leban *et al.* 2004), as a result of melting and flowing of amorphous material such as lignin and hemicellulose (Gfeller *et al.* 2004) as well as possible cell wall collapse. Indeed Leban *et al.* (2004) suggested that cell wall collapse was particularly prevalent in spruce, and might represent a major technology barrier to the process being applied to softwoods in general. The cell wall collapse helps explain the 190% density increase noted for spruce following frictional welding. Beech resulted in a narrower defined bond line (easily noted by its dark colouration), and was seen as indicative of avoiding cell wall collapse. Leban *et al.* (2004) also postulated that the presence of such narrow bond lines contributed to stronger mechanical bonds.

The energy input and the resultant heat generated at the welding interface play important roles in resultant bond strengths, based on the physical and chemical changes occurring. The physical movement of the samples undergoing welding also has a major influence on bond strength, given the constant formation and fracture of wood to wood bonds. Thus there needs to be a careful balance between the plasticisation stage, degree of movement exerted and the length of time the sample is held motionless during the bond formation stage.

One of the major drawbacks to the use of wood welding has been the reported instability of the bondline to moisture, with critical strength losses occurring. This can be partially linked to the hydrophilic nature of wood in general, with welded wood undergoing hydrolysis cleavage. One method that could help to overcome this issue is the use of wood with a reduced moisture affinity (*i.e.* a more hydrophobic timber). Another emerging wood technology of assisting this is wood modification, whereby the hydroxyl groups present within the wood undergo either a chemical reaction to block their activity (and possible interaction with water molecules), their removal from the wood structure through high temperature cleavage and inter- / intra-molecular rearrangements (in much the same way as might occur during the wood welding processes), or through a physical blocking by either surface treatments or cell wall bulking oligomeric agents capable of undergoing polymerisation once within the wood.

This paper will consider a range of modification treatments on the most common UK softwood species, Sitka spruce (*Picea sitchensis*), with regard to bonding *via* dowel rods and linear welding.

DOWEL WELDING IN WOOD

The use of vibrational lignobonding for the fixation of dowels has been proven (Pizzi *et al.* 2004), providing a means for fixing timber products, such as flooring, without the use of nails nor adhesive. A process has been developed (Pizzi *et al.* 2004) whereby dowels are inserted into pre-drilled holes of diameter smaller than that of the dowel to be used. The lignobonding is achieved through thermoplasticization during the rotational insertion of the dowel. Care has to be taken to prevent fracture of the dowel once solidification and bonding begins. An example of the type of bonding occurring is shown in Figure 1 (Ganne-Chedeville *et al.* 2005).

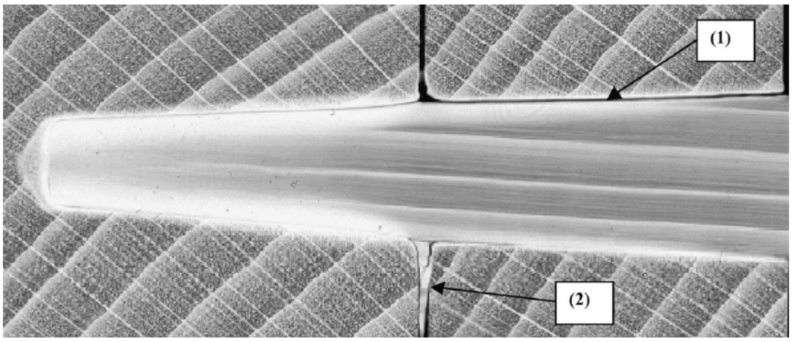

Figure 1: X-ray micrograph of dowel insertion (Ganne-Chedeville et al. 2005)

Figure 1 demonstrates the potential of bonding within beech, with the X-ray image providing evidence of regions where densification has occurred, as shown by white areas. The arrow (1) shows a microcrack, showing where lignobonding has not occurred or has occurred and has subsequently fractured due to excessive rotational torque. Arrow (2) shows where molten intercellular material has flowed in the fissure between the two blocks. The physical appearance of lignobonding is shown in Figure 2, when the process is applied to spruce.

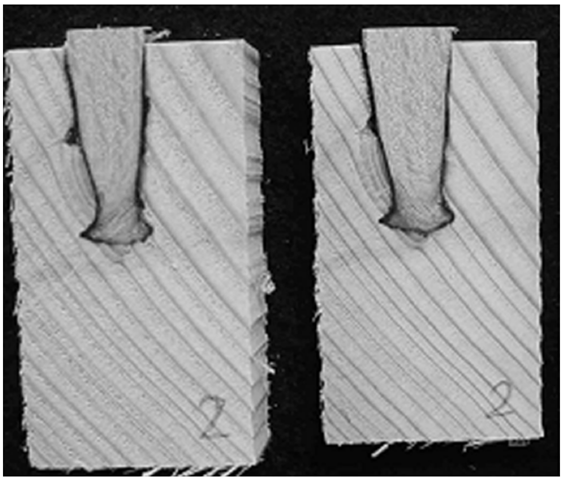

Figure 2: Cross-sectional profile of lignobonded dowel rod (Ganne-Chedeville et al. 2005)

One of the interesting aspects shown in Figure 2 is the compressive deformation undertaken at the dowel head, where the pressure of the dowel appears to have caused the area under greatest surface pressure (*i.e.* the smallest surface area) to undergo compression and flow. This is typified by the regions along the side of the dowel, where the growth rings have been compressively deformed. The use of such dowel bonding offers an interesting scope of application for softwoods such as spruce, since early results (Pizzi 2006) suggest that flooring using such methods may provide equivalent fixing strengths to those using conventional nailing. The use of dowel bonded systems may afford new market opportunities for a range of timber species within furniture manufacture.

LINEAR FRICTION WELDING

As its name suggests, linear friction welding occurs as a result of linear applied movement, stopping and changing direction on reaching maximum oscillation amplitude. The velocity and force applied are not uniform, but applied in a sinusoidal fashion. This results in the constant thermoplasticization of the wood interface, resulting in continuous melting, welding, fracture, re-melting and further welding and the microscopic level, provided the linear motion is maintained. As soon as the oscillation stops, the cyclic process stops at the welded state.

EXPERIMENTAL METHODS

Several sets of replicates were forwarded to ENSTIB for evaluation, these representing:

- Untreated Sitka spruce
- Acetylated Sitka spruce
- Heat treated Sitka spruce
- Furfurylated Sitka spruce

All the Sitka spruce samples were from a single forestry source, namely the Novar Estate, near Inverness, Scotland. The modification treatments were carried out by SHR Timber Research, Netherlands (acetylation), New Option Wood, France (heat treatment) and WPT, Norway (furfurylation). Each treatment was carried out as a batch treatment, and not optimised for the timber species.

Dowel welding of samples

The dowels used for the welding process were of beech, with the welding process producing the final bound dowels into pre-drilled holes. Insertion of the dowel was carried out using a conventional electrical hand drill. The welding process was maintained for 3 seconds, as longer times resulted in too high a torsional friction (caused by the constant formation and breaking of wood-wood interface welds), which resulted in torsional shear of the dowel.

From each set, samples were kept for the following tests as prescribed within BS 1204 (1993), which will be reported within this paper:

- 5 samples dowel-fixed *via* wood welding, then tested dry
- 5 samples dowel-fixed *via* wood welding, then tested wet
- 5 samples dowel-fixed *via* wood welding, then tested after 2 hours boiling (and subsequently tested wet)

Linear welding of samples

Linear friction welding of samples of dimension 20x20x50 mm was undertaken using a Branson 2400 system, operating at a head vibration frequency of 100 Hz. The welding amplitude used during all experiments was 3 mm, with a welding time of 3-5 seconds, followed with a holding time of 10 seconds.

The bound samples were tested as prescribed within BS EN 319 (1993), with groups of samples tested following:

- Conditioning for 2 days at 23 °C, 50% r.h.
- Immersion in water for 24 hours, then conditioned for 24 hours at 23 °C, 50% r.h.
- Immersion in water for 24 hours, dried at 103 °C for 24 hours, then conditioned for 2 hours at 23 °C, 50% r.h.
- No conditioning

The pieces have been tested in pure traction using standard laboratory testing machine (Zwick 1454) with a velocity of 10mm/min. Samples were determined failure occurred in the bond line (adhesive break) or in the wood (cohesive break). When a cohesive break was noticed, it meant that the material is weaker than the connection.

RESULTS AND DISCUSSION

Dowel welding

The analysis results of the dowel weld-insertion experiments are shown in Table 1, whereby the bond strengths of the dry (non-soaked), cold water soaked and boiling water soaked specimens are tabulated, along with the recorded densities of the samples.

Table 1: Overview of mechanical strength of dowels inserted into modified Sitka spruce

	Dry (non-soaked)		**Cold water soaked**		**Boiling water soaked (2 hours)**	
	Dowel bond strength (KN)	**Density (kg/m^3)**	**Dowel bond strength (KN)**	**Density (kg/m^3)**	**Dowel bond strength (KN)**	**Density (kg/m^3)**
Untreated	0.899	483	0.556	397	0.318	87
Heat treated	0.874	406	0.507	395	0.508	308
Acetylated	0.749	370	0.800	548	0.337	481
Furfurylated	0.373	517	0.443	498	0.552	461

Examples of the dowel fixation are shown in Figure 3. It can be seen that there is an increased fragility in the interface region between the modified wood samples and the dowel, which has led to areas of limited or no bonding through the welding process. The effect appears to be worst in the case of acetylated Sitka spruce. One possible reason for this could be attributed to the high degree of cell wall collapse noted following the acetylation process (since the process was not optimised for Sitka spruce), which is exasperated by the high rotational torque encountered during the dowel fixing.

The results from Table 1 exhibited a moderate degree of variability due to the need to manually hold samples during the dowel fixation process. Repeating the experiments with larger samples would allow uniform clamping of samples, which would hopefully reduce this variability.

It was interesting to note that for the dry and cold water soak results, there appeared to be a major, preponderant correlation with density for the untreated, heat treated and acetylated samples. The furfurylated samples did not conform to this prediction. Such a conclusion could not be reached for the boiling water soaked samples.

When considering the boiling water soaked samples, it is interesting to note that there appears to be a relative increase in the bond strength of the dowel within both the heat treated and the furfurylated samples, though considerably more in the latter case. A possible reason for the improvement noted for the furfurylated samples is the increased curing of furanic resins present within the wood as a result of the modification treatment. This further curing of the furanic resin will lead to a more tightly networked resin and thus will improve both the dimensional stability and hardness of the furfurylated joint as well as its its water repellancy. A similar effect has been noted with resorcinol resins when samples undergo boil soak tests, *i.e.* the results are an improvement on cold soak tests simply because the heat of the boiling water caused the resin to cross-link more.

Figure 3 : Fixation of dowels within Sitka spruce samples. Anticlockwise from top right: control, heat treated, acetylated, furfurylated

The results obtained, especially for furfurylated and heat treated spruce, represent a major step forward in the possibility of producing a water-stable wood welded joint. It is known that many modification treatments increase the hydrophobicity of the wood as a result of chemical transformations within the wood. For the heat-treated spruce, it can only be hypothesised that these transformations are stable within cold and boiling water. This reasoning appeared to be justified by the lack of movement (and subsequent retreat) either of the dowel or of the substrate, demonstrating this high dimensional stability. Work has been carried out previously on linear welding of heat treated timber (produced by Plato Hout BV, Netherlands), where good bond strength was noted, though no assessment of the bond following water soaking was carried out. Such water soaking of linear welded samples will be reported by the authors in due course.

Linear Welding

The results from the linear welding study are shown in Table 2. Due to the small sample sets, standard deviation was predictably high. The results from the glued samples were higher than those obtained for the welded samples, and yielded cohesive breaks when tested. However, the Sitka spruce samples tested confirmed previous experience, where this species was found to be very difficult to weld. Unlike the untreated Sitka spruce samples, all modified wood test specimens underwent adhesive failure. This may also be linked to the small sample size, as well as the non-optimised conditions used.

The results also showed that the weathering process (“wet” and “wet and dry”) decreased of the resistance of the modified wood welding bonds, compared to the glued examples. What was interesting was the fact that both the heat treated and acetylated sets yielded enough samples for a standard deviation to be determined. Untreated Sitka spruce only yielded a single sample suitable for testing after the wet and dry conditioning steps. This suggests that there is some degree of stability imparted to the weld in acetylated and heat treated wood.

Table 2: Overview of linear welding of unmodified and modified Sitka spruce samples

Wood treatment	Type of weathering	Number of samples	Average resistance [MPa]	Resistance Std. Dev. [MPa]	Type of break
none	Glued	5	2.39	0.92	cohesive
	No weathering	9	0.54	0.19	adhesive
	Wet	4	0.77	1.21	adhesive
	Wet + dry	1	0.26		adhesive
acetylated	Glued	5	1.15	0.34	cohesive
	No weathering	10	0.66	0.32	adhesive
	Wet	6	0.23	0.13	adhesive
	Wet + dry	6	0.28	0.18	adhesive
Heat treatment	Glued	5	1.15	0.44	cohesive
	No weathering	10	0.57	0.34	adhesive
	Wet	4	0.09	0.04	adhesive
	Wet + dry	4	0.17	0.17	adhesive
Furfurylated	Glued	4	1.37	1.37	cohesive
	No weathering	no welding			
	Wet	no welding			
	Wet + dry	no welding			

The lack of results for furfurylated samples conflicts the earlier hypothesis from the dowel rod experiments where it was postulated that furanic polymerisation might assist the welding process. Further studies need to be carried out to determine if any chemical bonding or alteration in polymeric form has occurred.

CONCLUSIONS

The fixation of dowels by wood welding technologies appears to be applicable to modified wood samples. Whilst there appeared to some degree of embrittlement of the drilled recess on insertion of the dowel, this might be due to weakening of the sample resulting from non-optimised treatment schedules. Water soak (cold and boiling water) tests showed reasonable retention of the welded bondline strength. For heat treated and furfurylated samples, this was higher than expected. In the case of furfurylated samples, this could be attributed to increased furanic resin during the boiling water soak process.

Results from the linear welding experiments with modified wood proved problematic, especially with furfurylated wood. This may be attributed to either the low number of replicates of the small dimension samples used. However this may also dispel the theory of furanic linkages suggested following the dowel welding. Further studies would need to be undertaken to prove this. The low values from untreated Sitka spruce also suggest this is not the best timber species to trial. What was noted was the ability of both the acetylated and heat treated samples to provide some degree of stabilisation to the wood weld, suggesting that, with optimisation, usable results may be obtained.

The results suggest that combining two emerging technologies (wood modification and wood welding) may result in a bondline capable of withstanding exposure to high moisture levels. This could open new possibilities into the use of wood welding.

REFERENCES

BS 1204 (1993). Specification for type MR phenolic and aminoplastic synthetic resin adhesives for wood. British Standards Institute.

BS EN 319 (1993). Particleboards and fibreboards — Determination of tensile strength perpendicular to the plane of the board. British Standards Institute.

Ganne-Chedeville, C., Pizzi, A., Thomas, A., Leban, J.M., Bocquet, J.-F., Despres, A. and Mansouri H (2005). Parameter interactions in two-block welding and the wood nail concept in wood dowel welding *Journal of Adhesion Science and Technology*, **19**, 1157–1174

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

Leban, J.-M., Pizzi, A., Wieland, S., Zanetti M, Properzi M and Pichelin F (2004). X-ray microdensitometry analysis of vibration-welded wood. *Journal of Adhesion Science and Technology,* **18**, 673-685.

Pizzi, A. (2006). Private communication to Dennis Jones.

Pizzi, A., Leban, J.-M., Kanazawa, F., Properzi, M. and Pichelin F (2004). Wood dowel bonding by high-speed rotation welding. *Journal Adhesion Science and Technology,* **18**, 1263-1278.

Suthoff, B. and Kutzer, H.-J. (1997). *German Patent* DE 197 46 782 A.

Suthoff, B., Schaaf, A., Hentschel, H. and Franz, U. (1996). *German Patent* DE 196 20 273.