Many Roles of Wood Adhesives

Charles R. Frihart
Forest Products Laboratory
Madison, WI, 53726, USA
cfrihart@fs.fed.us

Introduction

Although wood bonding is one of the oldest applications of adhesives, going back to early recorded history (1), some aspects of wood bonds are still not fully understood. Most books in the general area of adhesives and adhesion do not cover wood bonding. However, a clearer understanding of wood bonding and wood adhesives can lead to improved products. This is important because wood bonding is one of the largest applications of adhesives and is important for efficient use of our forest resource and increasing the use of these green products.

Wood can be very easy to bond, but making the bonds durable against changing moisture, high temperature, and high loads can be difficult. All these conditions can be critical issues, especially considering that wood products are expected to last decades, if not centuries, without the adhesive changing in performance characteristics.

Making durable wood adhesives requires understanding the substantial differences between bonding wood and most other materials. These differences and some thoughts on specific adhesive performance are covered in this paper.

Durable Wood Bonding

One important aspect of wood bonding is the porosity of wood (1). Not only does it have interconnected cells into which adhesive can flow, but the cell walls themselves have the ability to absorb low molecular weight chemicals and in some cases to react with them. Filling the cell lumen with adhesive provides much larger mechanical interlocks than are available with surface roughness for most substrates. Absorption into the cell wall can provide micromechanical interlocks and interpenetrating networks. Although cell diameters (about 25 μm) limit filler particle penetration, adhesive polymers can fill the lumen. However, a disadvantage is that for very low viscosity adhesives, overpenetration can be an issue and lead to a lack of adhesive between the wood surfaces. In addition, the ability of wood to absorb small polar molecules reduces the chances that they will form weak boundary layers. On the other hand, less polar components of the wood (extractives) or adhesive can come to the surface and form weak boundary layers.

Another important aspect of wood is its nonuniformity (1). Wood is made up of parallel oblong cells, leading to differences in properties among the longitudinal, radial, and tangential directions of the substrate. Going out from the center of the tree, the pith, juvenile wood, heartwood, and sapwood make up the different domains of a tree cross section, and within each of these are rings of earlywood and latewood. Not only do these different domains have different physical properties, but also they often have different chemical properties. Upon planing, the thin-walled earlywood cells split open to give a large bonding area with exposed polar cellulosics for good bonding, whereas the thick-wall cells split in the middle lamella to give a flatter and harder-to-bond-to surface made up of mainly the less polar lignin (1).

Durable wood adhesives need to be able to accommodate large dimensional changes that occur when wood swells and shrinks with changing moisture conditions (1). As wood swells, strain can build up in the interphase region due to differences in dimensional changes between the adhesive and the wood. Two distinct classes of wood adhesives have different ways to distribute this strain (2). The most common class, rigid *in situ* polymerized adhesives, relieves this stress in many cases by distributing the strain through the wood interphase region. The other class, the more flexible pre-polymerized adhesives, can distribute the strain through the adhesive interphase. Failure to adequately perform either of these strain distribution processes can lead to high strains and subsequent failure zones. As wood dries, it shrinks back to near its original dimensions. These failure zones can expand and become more visible as delamination areas. A very important structural wood adhesive test is ASTM D 2559, which examines bond delamination using cycles of wood swelling and shrinking through fairly rapid water soaking and drying (3). These cyclical forces are enough to cause cracks in the wood and delamination of the bondline if the adhesive does not provide durable bonds. Thus, durability of the adhesive is highly dependent upon wood–adhesive interactions in the interphase and the swelling and shrinking characteristics of wood (4). The discussion below considers some of these surface issues, which are still not fully understood.

The literature for evaluating adhesive performance often does not consider the wood surface layer. Preparation of wood surfaces can play a critical role in adhesive performance due to chemically or physically weak boundary layers (5, 6). Chemically weak boundary layers can result from wood extractives migrating to the surface or from overheating the wood surface during drying or hot pressing, and can usually be evaluated by a simple water droplet spreading experiment (6). This problem can be solved by freshly preparing the surface (1). On the other hand, detecting a mechanically weak boundary layer usually requires microscopy. Due to its less obvious nature, it may

be causing more adhesion problems than normally anticipated.

Mechanically weak wood surfaces can have several causes (5, 6). One cause is physical crushing of the surface, especially by abrasive planing (Figure 1) or by too high of a bonding pressure (1). This occurs when more pressure is applied than the thin-walled earlywood cells can withstand. The strength of these cells is reduced due to deformation and fracture of the cell walls. A second cause is sanding dust or other dust accumulation on surfaces; many panel surfaces are sanded to obtain final thickness or to remove discolored or deactivated surfaces from hot pressing. A third cause is tearing of the surface that occurs during planing and sanding. Even carefully set fresh planer blades will lead to a torn and/or smeared surface that shows poorly attached fragments at different levels of magnification (Figure 2). A fourth cause, associated with high-density wood species, is cells becoming separated from one another due to the force of planing (Figure 3).

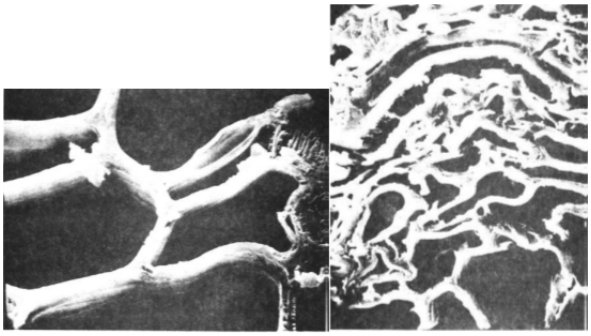

Figure 1. End-grain view of earlywood cells just beneath the surface of wood that was surfaced with (left) a properly sharpened and mounted hand-fed knife planer and (right) an abrasive planer using 36 grit belt.

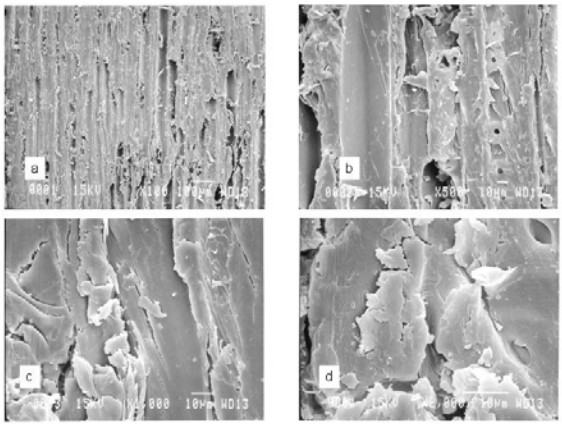

Figure 2. Scanning electron microscopy of yellow poplar tangential surfaces at four levels of magnification showing extensive fracturing of the surface and generation of weakly bonded fragments even with sharp planer blades.

Figure 3. Light microscopy image (40X cross section) showing a red phenol-resorcinol-formaldehyde adhesive flowing into tannish libriform separated cells of Ipe.

Results and Discussion

In addition to adhering to the wood surface, wood adhesives must often serve in a variety of roles to form a durable bond.

The first of these roles is minimizing the strain concentration at the interface between the wood and adhesive due to their differences in expansion/contraction characteristics with moisture changes. The *in situ* polymerized class of wood adhesives yields rigid polymers due their aromatic or pseudo-aromatic monomers and the extensive cross-linked morphology of the cured adhesive (2). Thus, the reduction in interfacial strain needs to be accomplished by reducing the swelling of the wood near the interface. Literature indicates that wood impregnated with phenol-formaldehyde (PF), melamine-formaldehyde (MF), or urea-formaldehyde (UF) has reduced swelling/shrinking capacity (7). Because it has also been shown that PF and MF adhesives have infiltrated into the cell walls adjacent to the interface (2), it is reasonable to assume that the strain differential between the bulk wood and adhesives is spread over the wood interphase portion of the bondline. This distribution of internal forces explains how these rigid adhesives can provide durable bonds despite dimensional change of the wood.

However, epoxies usually do not provide durable bonds when wood is exposed to moisture. They are a rigid *in situ* polymerized adhesive, but there is no literature evidence that epoxies can stabilize wood structure. It could be expected that the lower molecular weight amine curing agents would infiltrate the wood cell walls, but not the low-polarity, higher-molecular-weight epoxy resin. Thus, epoxies are not very likely to stabilize the wood surface. The evidence is that the epoxy fails in the adhesive and probably near the surface (8). Additional evidence supports this model in that wood species that swell and shrink less had more durable bonds with epoxy (4).

Because *in situ* polymerized adhesives have fairly low molecular weights, the applied adhesive should be able to flow into the wood structure and in some cases infiltrate

the wood cell walls to reinforce damaged wood structure. However, this is less likely to occur for the pre-polymerized adhesives. A proposal raised here is that the lack of repair of damaged wood surfaces may explain why polyurethane adhesives can provide good shear strength with bonded wood specimens under both dry and wet conditions, but the failure is mainly in the bondline rather than in the wood under wet conditions, contrary to the desire for the bond to be stronger than the wood. Given that both high wood failure and shear strength are important properties for meeting the existing ASTM D 2559 standard, the lack of wood failure has been a problem with gaining acceptance of polyurethane adhesives in structural wood bonding. Locating the exact failure location and cause could lead to improved polyurethane adhesives.

Following this line of thought, hydroxymethylated resorcinol (HMR) primer has been shown in at least three U.S. laboratories and several in Europe to be an effective primer for improving bond strength and durability with a variety of wood adhesives. On the other hand, despite studies in a number of laboratories besides the Forest Products Laboraotry, no definitive proof has been offered as to why it is such an effective primer (9). One prior hypothesis proposed that HMR was modifying the wood surface to reduce swelling and shrinking; another hypothesis proposed here is that it is repairing the damaged wood surface. This second mechanism would explain why improved adhesive properties were observed even under dry conditions in some tests. This hypothesis needs to be examined.

Conclusions

Adhesives for bonding wood are a large and growing market. Although advances have been made in adhesive chemistry to provide formulations that give good performance in many cases, good explanations for all observations are still not available. The discussion here is to highlight that not only do adhesives need to bond to the wood surface, but also they need to repair defects on and below the wood surface. Further development of analysis techniques and carefully planned experiments are needed to evaluate the hypothesis that repair of wood damage is important for adhesive performance.

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