Adhesive Penetration of Wood and Its Effect on Bond Strength

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Introduction

Woodworkers know that wood is porous in that adhesive flows into lumens for a mechanical interlock (1) and that wood absorbs water, allowing the use of water-borne adhesives. However, the anatomical aspects of wood that lend to its porosity are much more complicated and have a greater influence on adhesive performance than is normally realized or discussed. This porosity can have both positive and negative effects on adhesive performance. A greater appreciation of how porosity relates to adhesive performance is important in designing new and improved adhesive formulations.

Trees are living organisms, and the transportation of water and other nutrients within the tree is important for its survival and growth (2). The xylem cells need to have a high aspect ratio, with the long axis being in the longitudinal direction to provide for capillary flow of water up the tree. Pores from pits in the cells allow for cell-to-cell transfer of water, and rays allow for radial transfer of water. These channels also provide an avenue to move inorganic and organic nutrients around the tree. Although porosity often decreases as wood is dried for use in wood products, it is still more porous than most substrates. This porosity needs to be taken into account when examining adhesive performance.

Lumen Porosity

The most obvious aspect of wood is its cellular nature (2). The cells allow for rapid flow into the large earlywood lumens in softwood and vessel elements in hardwoods. There is much less flow into the much smaller lumens of the thicker-walled latewood cells. Because wood joints are usually bonded on the radial-longitudinal or tangential-longitudinal surfaces because these surfaces are usually not completely parallel to the wood grain, adhesive can flow into the obliquely-cut cells following the grain and allow for significant adhesive penetration away from the surface (Fig. 1). There has also been some demonstration that adhesives flow from cell to cell through the pits to flow into additional lumens. This transport through pits provides adhesive flow into adjacent cell lumens, creating a greater mechanical interlock via lumen filling. For flow into lumens, average and maximum extents of penetration can be measured (3). This lumen filling has often been studied when evaluating adhesive performance because cross sections can be used to readily measure lumen penetration. However, the variability of wood surfaces due to the uneven distribution in cell structures in wood leads to areas of high lumen filling and areas of low lumen filling. Examples of this include earlywood and latewood bands in softwoods and ring porous distribution of vessel elements in hardwoods. A question then arises: do areas of high penetration provide enough strength to make up for areas of low penetration? It has been shown that adhesives can flow into ray cells from the surfaces (3). However, it is not clear that this lumen filling by the adhesive in the wood actually improves the strength of bonded wood when subjected to wet conditions. Flow into the lumens alone will not swell the wood, nor is it likely to restrict wood swelling to any great degree.

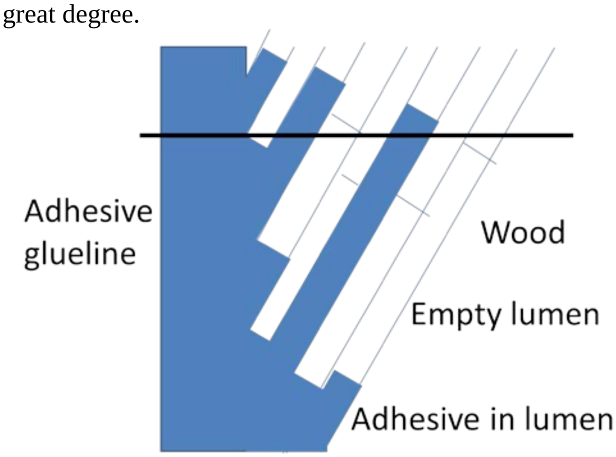

Figure 1. Flow of adhesive into lumens, with the horizontal line showing the cross-sectional cut.

One concern is if deep flow of adhesive into the wood lumens draws adhesive away from the glueline; this can lead to insufficient adhesive bonding the two surfaces and a starved glueline. In addition, this excessive flow may not contribute greatly to adhesive strength, leading to more adhesive being used than is necessary from a performance point of view. This is a very important aspect for wood bonding because the adhesive costs much more than the wood, and thus, excessive wood adhesive use can add considerably to the cost of the bonded product. These factors need to be evaluated by experimenting with the desired wood species because performance is hard to predict. Once applied, a water-borne adhesive will lose water into the wood, leading to increased adhesive viscosity, which reduces penetration into the wood.

An example where the adhesive usually does not provide moisture-durable bonds, despite adequate lumen filling, is with epoxy adhesives. In spite of providing good environmental resistance on many substrates, epoxies have been repeatedly shown not to provide satisfactorily bonded wood products when exposed to accelerated water exposure tests. Although an epoxy adhesive provided good lumen filling and had good dry strength, the bond had poor wet strength (4). Thus, although mechanical interlocking is most likely important to wood bond strength for dry bonds, it is not always sufficient for good wet bond strength.

Cell Wall Porosity

The other type of wood porosity relates to the cell wall itself. Although flow into lumens is relatively easy to detect and quantify, infiltration of cell walls is neither of these, but is probably more important than flow into lumens. Lower molecular weight and polar components are known to infiltrate the cell wall structure and swell the wood due to bulking effects. If there are reactive groups on these components, the groups may react with cell wall polymers (mainly lignin and hemicellulose) or self-react. The bulking of, and reactions within, cell walls will reduce the amount of cell wall swelling that takes place when exposed to moisture. The reduced swelling of wood will lower the strain at the interface due to wood swelling; thus, less force is applied to the adhesive at the interface. Consequently, designing an adhesive so that it contains low molecular weight and reactive components that can infiltrate the cell wall should benefit the adhesive performance.

This infiltration of the cell wall is a feature of *in situ* polymerized adhesives (4) in that those with sufficient amount of low molecular weight adhesive components usually have good durability, whereas higher molecular weight adhesives provides poorer performance (5). Many of the *in situ* polymerized adhesives are known to infiltrate the cell wall and provide reduced swelling under wet conditions. Reduced swelling in the wood interphase leads to less interfacial stress, and thus more moisture-durable bonds. Consequently, many *in situ* polymerized adhesives use both lumen filling and cell wall infiltration to provide durable bonds, whereas pre-polymerized adhesives are limited to lumen filling to provide durability. Although some methods can be used to quantify the amount of adhesive in the cell wall, most of these require labelling of the adhesive; thus new, simpler methods are needed to measure cell wall infiltration (4).

Lumen volume varies greatly between wood species, but it is not known how much cell wall porosity may vary between species, or even between cell types. It is generally understood that density of the cell wall is about the same from species to species; thus, differences in density between species must be related to differences in lumen volume. In general, higher wood density leads to greater dimensional swelling and swelling forces in the wood (2, 6).

The unusual porosity of wood plays another important role in making for a distinctive performance of adhesives in bond formation with wood. The ability of wood to absorb small molecules like water allows for the use of water-borne adhesives; this is what makes wood bonding a more green process compared with processes that depend upon solvent-borne adhesives. Additionally, the ability of small polar molecules to infiltrate cell walls is not only limited to water but also includes components containing amines, alcohols, thiols, acids or similar polar groups (7). Normally any low molecular weight components are of concern because they can migrate to the interface and create a weak boundary layer between the bulk adhesive and the bulk adherend (8). This absorption process is particularly valuable when these components are added to decrease the amount of water in the formulation so as to reduce steam pressure during hot pressing of composites, but hopefully not reduce adhesive strength. This method has been used to reduce the amount of water with soy-based adhesives without increasing viscosity. If these additives did not penetrate the wood, the final adhesive glueline would be too soft from plasticization to have good strength Another example of this process is with ultra-low formaldehyde emitting urea-formaldehyde (ULEF-UF) adhesives, which are usually made with a late addition of urea to absorb any free formaldehyde. Normally this added urea would weaken the adhesive strength, but removal of much of it from the glueline most likely contributes to the strength of these ULF-UF adhesives.

Conclusions

The unusual porosity of wood makes it quite different from other substrates in that both the formulation of the adhesive and the bonding processes need to be particularly tailored for wood. In some cases the porosity is beneficial, but in other cases, it is not. Flow into the wood allows for more mechanical interlock and bonding area than is available with most substrates. However, this may allow adhesive to flow away from the glueline, leading to either a starved glueline or excess consumption of adhesives. Often the time that an adhesive sits on the surface is important either as open assembly time to allow water to evaporate and adhesive to penetrate into the wood, or closed assembly time for substrate-to-substrate transfer of adhesive and to allow the adhesive to penetrate the wood.

Not only does water from water-borne adhesives infiltrate wood cell walls, but some low molecular weight adhesive oligomers will as well, which will swell the wood. This is a very important aspect and needs to be considered in adhesive formulation. Infiltration into wood cell walls is good in that it allows the use of water-borne adhesives. Additionally it provides some adhesives the ability to modify surface cells and reduce swelling under wet conditions and repair damaged wood surfaces. It also allows some low molecular weight additives to move from the adhesive into the wood, making the adhesive stronger without plasticization by the additives, which otherwise would soften the adhesive.

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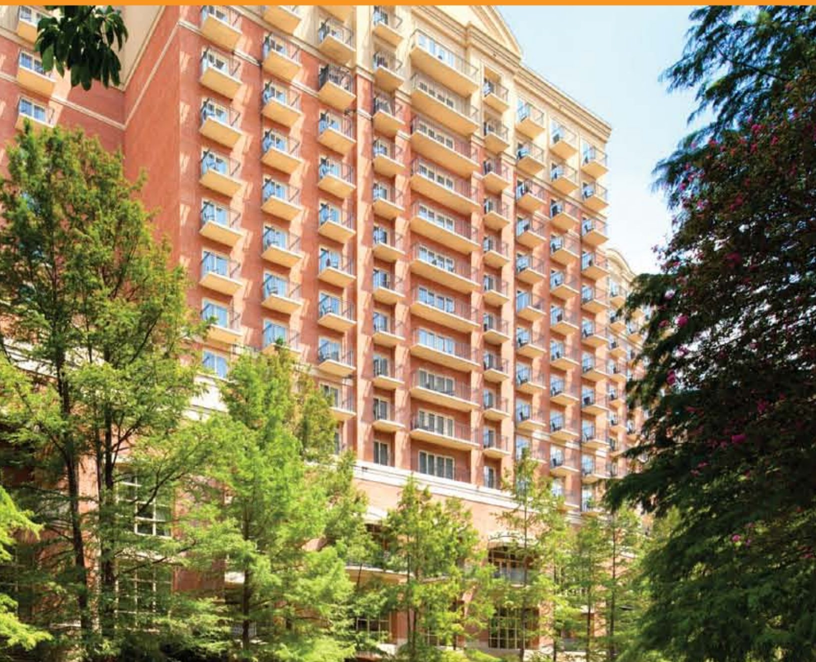

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