WOOD ADHESIVES

Vital for Producing Most Wood Products

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Image on left: Panel products (particleboard, plywood, fiberboard, and oriented strandboard from top to bottom) that would not exist without adhesives.

A MAIN ROUTE FOR THE EFFICIENT UTILIZATION OF WOOD RESOURCES IS TO REDUCE WOOD TO SMALL PIECES AND THEN BOND THEM TOGETHER (FRIHART AND HUNT 2010). ALTHOUGH HUMANKIND HAS BEEN BONDING WOOD SINCE EARLY EGYPTIAN CIVILIZATIONS, THE QUALITY AND QUANTITY OF BONDED WOOD PRODUCTS HAS INCREASED DRAMATICALLY OVER THE PAST 100 YEARS WITH THE DEVELOPMENT OF NEW ADHESIVES AND WOOD PRODUCTS.

A main route for the efficient utilization of wood resources is to reduce wood to small pieces and then bond them together (Frihart and Hunt 2010). Although humankind has been bonding wood since early Egyptian civilizations, the quality and quantity of bonded wood products has increased dramatically over the past 100 years with the development of new adhesives and wood products. An early driving force for wood bonding was the use of rare wood species as decorative veneers, which contributed to the importance of adhesives being used for furniture assembly for many centuries. Later on adhesives started being used for glulam and plywood production. All these wood products were made initially with protein adhesives derived from natural sources. Starting in the mid 20th century, synthetic adhesives were developed that provided lower cost and more moisture-durable products. These synthetic adhesives not only replaced the protein adhesives in existing applications, but also enabled wood product producers to achieve higher production efficiencies and meet the aesthetic requirements of the marketplace, while maintaining the necessary levels of product strength and durability.

Traditional structural products such as exterior plywood and glued laminated members use laminating adhesives that require high moisture resistance in-service. In some newer products, the adhesive is used in the form of droplets (e.g., resins, binders) between particles, strands, and fibers rather than as a film for lamination. Binder adhesives allowed for the development of wood composites, such as particleboard, oriented strandboard, and medium density fiberboard. These panel products would not exist without adhesives (examples are shown in Figure 1). The development of a more sophisticated engineered wood product, such as the wooden I-joist, was also aided by the availability of new or improved wood adhesives. The commonality between all these panel applications is that adhesives allow for more efficient use of wood resources by using small-diameter timbers that are of insufficient quality to be used for solid lumber, thus providing greater strength for a given mass of wood. Additionally, advances have enabled the development of adhesives that are more tolerant of the inherent variability in wood (e.g., moisture content, species), plant conditions (e.g., temperature, pressing pressure), and production rates. These advances can turn an impractical engineered wood product manufacturing operation into one that is commercially viable.

Although wood adhesives have been available for decades to meet existing product needs, new wood products (and changes in building codes and other regulations) have led to the need for new and improved adhesives. Newer products include engineered wood flooring and oriented strand lumber. An example of changes in regulations is the lower formaldehyde limits established by the California Air Resources Board (CARB). Interest in wood adhesives was demonstrated by the 206 researchers from 27 countries who attended the 2009 International Conference on Wood Adhesives in South Lake Tahoe, Nevada, despite the difficult economic climate. Papers from this conference are available from the Forest Products Society (Frihart et al. 2010) and cover environmental aspects, new types of bonded products, and advances of wood adhesion science and engineering that are discussed in the rest of this article.

DURABILITY AND STRENGTH OF BONDED WOOD PRODUCTS

Most adhesives will bond wood well according to laboratory strength tests at ambient temperature and humidity. However, commercial use of an adhesive requires using specific wood species to provide a strong bond; to resist creep, moisture, and temperature effects under conditions compatible with manufacturing operations; and to do so in an economical and environmentally acceptable manner. However, balancing all these factors can limit the number of acceptable wood adhesives for each bonding operation.

Wood is usually low in price on a strength-to-weight basis compared with most other common materials; thus, forming economical bonds while providing sufficient strength is important to keep wood products competitive. Many adhesives commonly used in other applications such as the automotive or aerospace industries are too expensive for typical wood bonding, with less than a dollar per pound being preferred. However, higher cost adhesives can still find a role if they can be used at a lower application level (adhesive weight per wood weight) or provide special properties. The price of the wood and adhesive is only part of the cost equation, with other factors being production issues, such as the rate of curing, ease of application, ability of a single adhesive formulation to bond a variety of wood species, and sufficient tack to provide enough green strength for handling the wood composite prior to final bonding. Polymeric diphenylmethane diisocycante (pMDI) is an example of a higher cost adhesive that is more effective at lower adhesive levels and less sensitive to furnish moisture. An example of a special property attribute that can increase production costs is the need to meet low formaldehyde emission limits. In this case, either ultra-low-emitting formaldehyde (ULEF) resins or, preferably, no-added formaldehyde (NAF) adhesives may command a premium price for interior products. Another important part of the cost equation involves the conversion costs. This is defined as the cost to "convert" the starting materials (wood, adhesive, etc.) into the finished bonded wood product, or composite. Adhesives that use lower cure temperatures or shorter cure times can significantly reduce the initial capital and ongoing cost even if the cost per pound of adhesive is the same or higher. In addition, in some processes, products without sufficient green strength or tack may not affect the final adhesive performance but can add to the cost of the product because material is lost. Adhesives that are easy to work with and can bond a variety of wood species will improve productivity. Consequentially, conversion or production costs need to be considered along with the cost of the adhesive.

In addition to cost, the structural behavior is an important issue for adhesives used in engineered wood products. The structural assessment generally consists of determining whether the adhesive will form a bondline of sufficient strength and whether the bondline will resist deformation under long-term static loads ranging from books on a loaded bookshelf to the weight of a house on a structural beam. This generally requires that the adhesive have sufficient cross-linking of the polymer chains so that they do not slide past each other when exposed to external forces. In general, any measurable creep is undesirable for many adhesive applications.

Another important performance criterion for most wood bonds is resistance of the bond to dimensional changes in the wood caused by wood moisture fluctuations. The specific moisture-resistance test depends upon the particular product and end use. These tests typically involve measuring the strength of water-soaked bonded assemblies, the strength of the product after soaking and drying cycles, or degree of delamination after soaking and drying cycles. One area of change for structural applications was the adoption in Canada of the standard CSA O-112.9 in 2004 (CSA). This new Canadian standard created differences between the structural adhesive requirements in Canada and the United States, where ASTM Specification D2559-09 is the standard (ASTM). These standards are important because they are used in structural wood products standards and building codes. Currently, efforts are in progress to align or harmonize D2559 with CSA O112.9 and O112.10 (CSA). The approach taken in Canada was to establish two moisture service categories—one for full exterior moisture exposure and another for inadvertent moisture exposure, but otherwise protected from the weather. The latter category is also referred to as "limited moisture exposure." The fully exterior durability covers products used outside or in high humidity indoor applications, such as with pools or water parks. The limited moisture exposure covers products that are normally protected from exterior exposure but may get wet during shipment of the bonded products or building construction.

Recently, assurance of the performance of bondlines at temperatures corresponding to fire exposure conditions has been of interest. These temperatures are considerably higher than the temperatures traditionally used to assess the thermal performance of bondlines. Whereas the temperatures for fire conditions are significantly higher, they are for much shorter durations (e.g., 10 minutes to several hours for fire, as opposed to days or weeks for warm environment creep tests). The expectation is that the bondlines in bonded wood products intended as substitutes for solid wood products of approximately the same size would have similar behavior under fire conditions as would solid wood. This has led to the recent ASTM standard D-7247 (ASTM) that requires the adhesive bond to retain nearly as much strength as the wood when exposed to fire temperatures just below the charring temperature of wood (Figure 2). This subject is still being debated, as others have maintained that because the char and thermal insulating character of wood limits the temperature in the bondline, lower exposure temperatures are more realistic. For papers on heat resistance, see Yeh et al. (2006), Richter et al., (2006), and Källander and Lind, (2006), Tannert et al. (2010), Richter and Lopéz-Suevos (2010). Ju et al., (2010a, 2010b) and Hunt et al. (2010).

Samples after ASTM D-7247 heat resistant test of an adhesive that still gives wood failure making it likely that the bonded product will pass a fire test (left) and one that does not making it likely that the bonded product will not pass a fire test (right).

Wood properties also play an important role in the performance of the adhesive bondline. Higher density woods are generally harder for the adhesive to penetrate and are less likely to fracture under load; thus failure is more likely to be within the adhesive rather than in the wood. Additionally, higher density wood generally swells more when exposed to higher moisture levels, creating more stress on the bondline. Thus, the adhesive needs to be tested with the wood species of interest under typical bonding conditions. With greater interest in the use of some tropical and chemically modified woods to provide greater moisture durability of the wood product, adhesives have to be optimized for bonding these woods.

Adhesives are used to bond wood in many ways and under many different conditions. These include the following:

1. Adhesive layers for plywood, engineered wood flooring, and glulam, other laminated beams, and surface veneers bonded onto particleboard and fiberboard cores
2. Binders (adhesive spots) for oriented strandboard, particleboard, and fiberboard
3. Adhesives for finger jointing, webbing for I-beams, and other structural applications
4. Adhesives used in the assembly of furniture and cabinets, bonds to plastics, metal and cement, and other non-structural applications

Adhesives need to be tailored for not only these different applications, but may need to be varied for specific plant operating conditions, especially differences between winter and summer conditions. Thus, adhesive manufacturers often need to make specialty adhesives at commodity prices. The best source of information on adhesive selection and permitted end use conditions is usually the adhesive manufacturer. They can recommend not only the best adhesive, but also the optimum wood and environmental conditions so that decisions can be made as to whether effort should be directed at controlling these conditions.

ENVIRONMENTAL IMPACT OF ADHESIVES ON WOOD PRODUCTS

Formaldehyde emissions from wood products have been driving many changes in the wood adhesives market. In the 1980s, emission limits for wood products were set as voluntary standards in the United States and Europe. Although permissible emission levels from wood composites were made more stringent in Europe and Japan since that time, levels were static in the United States until the adoption of regulations by the California Air Resources Board (CARB) (Table 1) and adoption of these standards nationwide in 2010. Authors that addressed formaldehyde emissions in *Wood Adhesives 2009* (Frihart et al. 2010) include Williams, Ruffing et al., Birkeland et al., Belloncle et al., Ferra et al., Đurkić et al., Schmidt and Holloway, Wescott et al., Athanassiadou et al., and Allen et al. The CARB standards led to two new product classifications of no-added formaldehyde (NAF) and ultra low emitting formaldehyde (ULEF) for interior adhesives. The development of NAF and ULEF, most notably the low-emitting class of urea-formaldehyde adhesives, has been rapid because of the short time frame to meet the strict emission limits. The transition to these lower emission regulations is being phased in by product type at two levels. These levels are referred to as the CARB-I and CARB-II levels. The more stringent CARB-II emissions are proving more difficult to meet and are most likely to result in increased adhesive costs and higher panel costs to the consumer. These regulations will apply to not only the initial wood products, but eventually the final products, such as furniture and cabinets. The difficulty in using some of the ULEF-UF, or the desire to use non-UF or even no added formaldehyde (NAF) adhesives, has led to increased opportunities for soy, poly(vinyl acetate), and isocyanate adhesives. These adhesives are, generally, more expensive on a weight basis than traditional UF resins, but do not emit formaldehyde. The term NAF is used rather than "formaldehyde-free" because no totally formaldehyde-free wood products exist, as wood itself contains and emits some formaldehyde. This has been referred to as "native formaldehyde" with the level depending on wood species, exposed wood surface, and heat exposure, such as with hot pressing. However, composites made with soy adhesives, for example, have been shown to emit less formaldehyde than no-adhesive wood composites because adhesives have the ability to scavenge some of this native formaldehyde (Birkeland et al. 2010).

Table 1—Phase 1 (P1) and Phase 2 (P2) formaldehyde emission standards for hardwood plywood (HWPW), particleboard (PB), and medium-density fiberboard (MDF)[a]

	P1 and P2 emission standards (ppm)				
Effective date	HWPW-VC	HWPW-CC	PB	MDF	Thin MDF
January 1, 2009	P1: 0.08	—	P1: 0.18	P1: 0.21	P1: 0.21
July 1, 2009	—	P1: 0.08	—	—	—
January 1, 2010	P2: 0.05	—	—	—	—
January 1, 2011	—	—	P2: 0.09	P2: 0.11	—
January 1, 2012	—	—	—	—	P2: 0.13
July 1, 2012	—	P2: 0.05	—	—	—

[a]Based on the primary test method (ASTM E 1333-96 (2002)) in parts per million (ppm). HWPW-VC = veneer core; HWPW-CC = composite core.

In addition to these more stringent formaldehyde regulations that alter adhesive use, development of green building certification has also affected wood products (Ruffing et al. 2010, Cribb 2010). Some green certification programs favor adhesives that do not contain UF. These programs are in a state of flux, as several different green building certification systems are currently in use.

As new wood products and standards are developed, they will continue to influence the types of adhesives that come to market. Overall, the wood adhesive market is likely to grow as more solid wood products are replaced by bonded wood products as a way to most efficiently use our wood resources.

LAMINATING ADHESIVE

Laminating adhesives are applied as a continuous layer of adhesive between two wood surfaces, the most familiar type of adhesive bond. The layers can be bonded parallel to the grain as in laminated veneer lumber or orthogonal to the grain as in plywood or engineered wood flooring (EWF). EWF is an example of a newer market replacing solid wood or non-wood flooring products. EWF allows more efficient use of wood by gluing small pieces together and using a lower quality of wood or composite for the core with high-quality wood reserved for the surface. Moreover, the orthogonal orientation of the EWF assembly affords a product of superior dimensional stability and less stress cracking than solid wood. Use of a variety of wood species and bamboo, in addition to the need to lower formaldehyde emission levels from these products, has led to not only new wood products but also has driven development of new adhesive formulations.

Although not a typical laminated product, finger joints have an adhesive layer between the two wood surfaces and have shown strong market potential for adhesives that join short, defect-free pieces into longer products, thus increasing their marketability. Finger jointing has been used to make wall studs after removing defective sections, but even more important is the use of finger joints to make long veneer pieces for laminated veneer lumber and flanges in wooden I-beams. With the extensive use of adhesives for assembly of both webs and flanges, manufacturing of wooden I-joists is essentially a continuous process enabling I-joists of any length to be manufactured with minimum waste. Use of adhesives has allowed engineered wood products to replace solid wood joists made of high-quality timber. Such products may use lower quality species that are typically not used in production of sawn lumber. The ability to use our forest resource for engineered wood products helps keep wood products competitive with other construction materials, such as steel and cement.

For laminating wood, phenolic adhesives have been highly effective in producing bonds that are durable with good resistance to decay, moisture, and heat, but they are dark in color. The relatively expensive phenol-resorcinol-formaldehyde resins cure at room temperature, whereas less expensive phenol-formaldehyde resins require heat curing. Melamine-formaldehyde and polyurethane adhesives are lighter colored and cure at room temperature, but available formulations do not appear to give equal performance to phenolic adhesives under standard heat- and moisture-resistance tests. Researchers still disagree on whether these latter adhesives have sufficient durability to provide moisture and heat resistance, particularly in cases where in-service environmental conditions are not well defined or controlled. Some have argued that the standards in the United States and Canada are too severe and may exclude adhesives that would perform adequately in-service. Given the importance of structural integrity in buildings, the more conservative approaches have generally prevailed.

No significant changes have been made in adhesives used for exterior plywood or laminated wood for structural applications (glulam or laminated veneer lumber), but a new test method D7247 (ASTM), as mentioned previously, requires the high temperature resistance of adhesives to be determined. The concern is that the heat of a fire could soften or degrade the adhesive so that the wood member fails at a lower temperature than a solid wood member, creating a hazardous situation for fire fighters. This standard not only applies to face-laminating adhesives, but also to finger jointing adhesives used in structural elements. This has caused replacement of poly(vinyl acetate) for finger jointing and caused some other adhesives to be reformulated to increase their heat resistance. Other methods for assessing the performance of adhesives at elevated temperatures are the ASTM standard practice D7374 and D7470 (ASTM). These two standards use an ASTM E119 fire resistance test of a full-scale load bearing wall assembly framed with multiple finger jointed stud members. Toward the end of the test, finger joints are subject to elevated temperatures and increasing bending loads, as a good portion of the depth of the stud, starting with the face closest to the fire, is converted to char. The American Lumber Standard Committee uses these standards as a basis for determining whether a finger joint adhesive qualifies for the Heat Resistant Adhesive (HRA) designation. (http://www.alsc.org/untreated_gluedlbr_mod.htm)

A new area for wood adhesives is cross laminated timber (CLT). This technology has been developed mainly in Europe, but is now being considered in North America. The CLT can be used as a non-stiffened (e.g., no ribs) plate for floor, roof, or wall applications. Because it is prefabricated and cutouts can be made and edges finished using a CNC machine, it lends itself to the rapid construction of multi-story buildings. Multiple layers of wood create a thick wood panel that has good fire resistance, especially with added insulation. When adequately connected, CLT panels also provide the structure with good lateral resistance to extreme wind and seismic events. Similar to thick plywood, these products could further expand the adhesive market. However, given the newness of the technology, it is hard to judge if these products will have good market acceptance in North America.

BINDER RESIN

The single largest application of wood adhesives is in bonding together wood strands, particles, and fibers into composite panels; the very nature of these products requires cost effective and high-performing adhesives. Whereas the previous section focused on adhesives used in a layer between well-defined wood surfaces, binders are usually not discrete films and are often droplets on the surfaces of wood particles, sometimes referred to as "spot welds." Although adhesive application processes can vary between strandboard, particleboard, and fiberboard, further processing involves blending steps that spread adhesive droplets over the wood surface.

Subsequent hot pressing compresses the product, thus increasing penetration and spreading and ultimately curing the thermosetting adhesive. Hot pressing also forces moisture to move from the surface to the core of the composite, creating an internal steam pressure that can generate blows or delamination problems if the adhesive has not cured sufficiently to resist this internal pressure. Therefore, the adhesive requirements for the face and core resins are often quite different:

1. Face resins operate under higher temperatures and drier, higher wood density conditions and should not adhere to the platens, whereas
2. Core resins operate under lower temperature, and wetter, lower wood density conditions.

During pressing, the face (top and bottom of the bonded panel) comes into contact with hot platens before mat consolidation. Thus, the face adhesive should not cure before wood completely consolidates on the surface. On the other hand, the core sees the highest moisture and steam pressure as well as the lowest temperatures, which require a very fast curing adhesive. These complex dynamics have led to a large number of studies that analyze curing and formation processes and that develop models, which simulate these complex processes (Dai et al. 2005, Lanvermann and Theomann 2010, Dai et al. 2010, and Narin and Le 2010).

FOSSIL FUEL ADHESIVES

Fossil fuels (natural gas and petroleum) are important feedstocks for making adhesives (Winterowd 2006). Natural gas is used to make pMDI adhesives, as well as the formaldehyde used in amino adhesives and phenolic adhesives. Petroleum is also used in making phenolic and pMDI adhesives. These adhesive prices depend upon the price of petroleum and natural gas that often fluctuate relative to each other and other raw materials, such as biomass feedstocks. Adhesive price continues to be a major issue in adhesive selection for bonding wood products. Since their inception, some adhesive systems have not changed a great deal, but others have seen considerable change. Given the good performance of phenolics, they have stayed relatively constant, except for efforts to reduce cost and accelerate cure. Continued improvement in the cross-linked poly(vinyl acetate) and polyurethanes are leading to additional use of these products. Changes in formulations of these adhesives can lead to products with a wide range of properties, allowing them to be tailored to specific applications.

After many years of relative stability, urea–formaldehyde (UF) adhesives are undergoing considerable change to meet new formaldehyde emission standards in the United States. To reduce formaldehyde emission, UF producers can alter the order of addition, reduce the formaldehyde-to-urea ratio, add melamine or melamine–formaldehyde, or add formaldehyde scavengers. The latter two options can add considerably to the cost of the adhesive. Excessive reduction of formaldehyde does, at some point, lead to a significant loss in strength, durability, or operating window of adhesives. Some fossil fuel adhesives are being modified to contain more biobased content to make the adhesives more environmentally friendly or "greener" and lower in formaldehyde content. Some adhesives have for years contained biobased fillers, such as walnut shell flour, and extenders, such as wheat gluten. In plywood, these materials can improve gap filling and tack properties. It is not clear if the newer biobased additives give performance improvements or are just make greener adhesives. Among the commercial products are soy with poly(vinyl acetate) for Multi-bond by Franklin adhesives (Columbus, OH) and EcoBind by Momentive Specialty Chemicals (Columbus, OH).

BIOBASED ADHESIVES

Although protein adhesives were widely used in the first part of the 20th century, most of the older highly alkaline systems were replaced by fossil fuel-based systems, except for specialty applications such as fire doors. Adhesives from renewable resources have been of interest for many years, but none had the performance and production cost to make an impact in the wood adhesive market until soy flour adhesives, using a polyamidoamine–epichlorohydrin (PAE) resin, were developed (Li 2004). This technology was implemented by Li working with Hercules, a manufacturer of PAE, and Columbia Forest Products (Greensboro, NC), a major producer of decorative plywood. This technology was recognized by the American Chemical Society in 2007 by its Green Chemistry Award. Like most new adhesive systems, important strides have been made in advancing the soy–PAE products. The Ashland Hercules Soyad® (Ashland Hercules Water Technologies, Wilmington, DE) products are a major part of the decorative plywood market and are also used commercially in engineered wood flooring and particleboard.

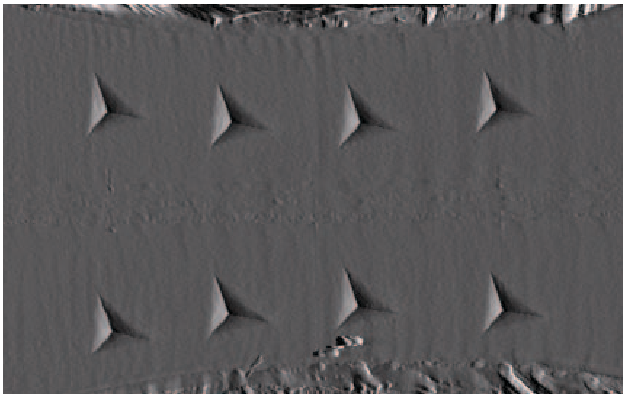
Other adhesive systems have been developed using soy proteins in combination with other adhesives. Soy flour can replace about half the phenol in basic or neutral formulations that meet the performance requirements for the face adhesives of oriented strandboard (Wescott and Frihart 2008). For the adhesive to meet strength and durability requirements at these higher soy levels, it needs to become part of the adhesive network rather than just being used as a filler. Although soy flour is abundant and of low cost in the United States, wheat flour is a more likely feedstock in Europe.

In addition to studies on proteins, investigations continue into aromatic biobased materials. Tannins are used as a partial replacement of phenols because of their good reactivity, but the volumes are small because of limited availability. Lignin continues to be evaluated as a partial replacement of phenols, but the volume used in wood adhesives has been low because of limited reactivity. However, the amount of lignin that is available at fuel price is substantial and is ever increasing. New biorefinery technology may provide more reactive lignins in the future. Non-protein adhesives have been reviewed (Pizzi 2006).

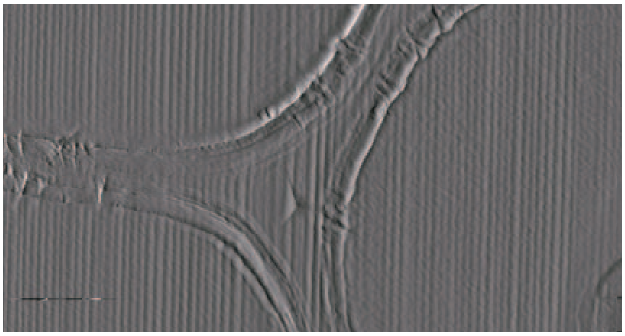
ADHESIVE BOND SCIENCE AND ENGINEERING

The amount of existing wood adhesive literature is substantial going back many decades and broadly covers adhesive chemistry and properties, wood surface preparation, and bonded wood properties with emphasis on macro-mechanics. Although understanding these aspects is important for producing good bonds and bonded wood products, they are of limited help in understanding the detailed processes taking place in bond formation and failure. With development of new analytical methods, research has been moving in the direction of a better understanding of adhesive–wood interactions and micro-mechanical analysis to look at stress-strain behavior. The understanding of wood bonds has trailed other areas of adhesion science, such as bonding to metals and plastics, because of the complex nature of wood morphology and chemistry and the problems in using some of the sophisticated analytical techniques with wood.

For many years, analytical tools available for analyzing wood bonds were mainly limited to optical and scanning electron microscopy. These tools were able to identify adhesive penetration (both lumen filling and cell wall infiltration) and provide information on fracture loci (Kamke and Lee 2007). Gindl and others in Austria have shown that ultraviolet microscopy (Gindl et. al. 2003), nanoindentation (Konnerth et al. 2007) (Figure 3), and scanning thermal microscopy (Konnerth et al. 2008) can provide information about adhesive infiltration of cell walls. Combining solution-state two-dimensional nuclear magnetic resonance spectroscopy with broadband spectroscopy using a nanoindenter, some hypotheses on the mode of adhesion with isocyanates were shown to be invalid under typical bonding conditions, while supporting another hypothesis (Jakes et al. 2010, Yelle et al. 2010). A number of research groups around the world have expanded the use of fluorescent microscopy of adhesives from solid wood samples to wood particles and fibers. This information has been important in understanding distribution issues that are crucial to the performance of composites (Zhang et al. 2010, Grigsby and Thumm 2010).



SCWL



CCML

Nanoindentation of wood in the secondary cell wall layer (SCWL) and in the compound corner middle lamella (CCML) using the techniques of Joseph Jakes of the Forest Products Laboratory.

Although much of the emphasis on adhesives comes from knowing and altering formulation chemistry, adhesives are used for their ability to mechanically and physically hold materials together. Mechanics of bond strength is an important area of continuing research as more sophisticated methods continue to advance our understanding of how forces are transferred from one wood piece through the adhesive to another wood piece. A large amount of research is focused on developing models for making composites. As stated previously, understanding wood composite processes is difficult because of thermal, moisture, and density gradients. These influence the cure and, therefore, the strength of the adhesive bond. Modeling has been important toward understanding the complex dynamics of these processes.

OPPORTUNITIES

Given the generally higher cost of adhesives compared with that of wood and the cost sensitivity of large-volume wood products, it is essential to develop robust adhesives that enable the bonded wood product to be cost competitive. Many adhesive formulations have shown that they can produce wood products that meet the needs of consumers and provide good long-term performance, leading to a considerable increase of bonded wood products over that of solid wood products. However, wood adhesives continually need to evolve to meet new product requirements and to deal with changes in regulatory and consumer preferences. Although the majority of products are derived from fossil fuels, there are areas of growth for biobased adhesives. Much of the work has been on adhesive development, but to both support the development of new adhesives and ensure that the best available adhesive technology is specified for the end use application, we need to better understand the fundamental science of adhesive properties and adhesive–wood interactions with respect to performance of bonded products.

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