WOOD-BASED COMPOSITES AND LAMINATES

Various trees provide many things of use to people in addition to wood and paper products, such as heating and cooking fuel, fruits, nuts, chemicals, and useful drugs. Trees provide homes for wildlife and birds as well as beautiful scenery. Perhaps most importantly, they use sunlight to convert carbon dioxide from the air and water as the basic building blocks to produce their woody substance, bark, and leaves. A by-product of these photosynthesis reactions is oxygen, which is emitted into the air. Thus, trees as well as all green plants are essential in maintaining acceptable levels of oxygen and carbon dioxide in the atmosphere.

As trees grow, cellulose molecules are produced. These molecules are long strands of 6- carbon ring structures attached end-to-end. They may have a length of as much as 1500 units. Many cellulose molecules are laid side-by-side to produce microfibrils. The microfibrils form the basic structure of the wood fibers. Most fibers develop so that their strongest, lengthwise direction is parallel to the vertical direction of the stem. A substance called lignin is formed to reinforce and bond the fibers to one another. As the tree grows, these layers of fibers develop outward and upward to form the stem of the tree. These natural, renewable structures (fibers and wood) are the basis of virtually all major uses of forest products.

As with all living things, trees have a finite lifespan. Only a few species will flourish for more than 100 years, the majority passing into old age at 30 to 80 years. Because wood, wood products, and paper make up such an important and integral part of our lives, it is equally important to have well-conceived forest management plans that provide for growth management, timely removals, and speedy regeneration. Only in this way can adequate supplies for future generations be assured. Fortunately, the United States is endowed with some of the best lands and climate for forest production in the world. Properly managed, these lands could supply the future needs not only of the United States but a significant portion of the needs of other parts of the world as well. In addition, these lands can provide significant employment and resultant contributions to the economy.

1. Historical Development

Wood is one of the oldest construction materials in human use and continues to be an extremely valuable material to this day. Wood is lightweight, strong, stable, easily worked and fastened, a good insulator, warm to the touch, and pleasing in appearance, among many other attributes.

Logs and rough beams were probably the first uses of wood, employed in large construction projects as soon as simple tools became available. Prior to the industrial revolution, sawn lumber was available only in limited quantities. Paper, also in small quantities, was made from cotton rags, or papyrus, the inner bark of some species of trees, or rice straw in China and Japan. The advent of large machinery allowed production of lumber as a commodity. The manufacture of large quantities of wood veneer followed quickly. The discovery of chemical pulping of wood to separate the fibers and lignin coincided with the availability of large machinery to make continuous lengths of paper. Thus, the wood products and paper industries began, without which a modern way of life would have been impossible to achieve.

The vast natural resources of timber in the United States, through the foresight of early foresters and political leaders, led to the availability of large quantities of lumber at reasonable cost. This abundance has made the United States the best-housed and most comfortable of all the areas of the world. However, in the conversion of timber to lumber or veneer, only about one-half of the volume of the log actually becomes lumber or veneer. The remainder is in the form of bark, slabs, edgings, sawdust, planer shavings, veneer round-up waste and clippings, veneer cores, and plywood trim waste. For some years, these residues were largely unused except for small amounts diverted to pulp and paper mills. Then, in the early 1900s, various developers and entrepreneurs began discovering new and useful products which could be made from these residues. Today (ca 1997), virtually the entire woody stem of the tree is converted to a family of wood and wood-based products. These developments have literally doubled, and perhaps with recycling, more than doubled the yield of usable products from a given volume of wood, contributing even more greatly to the comfort of ordinary people and to the economy. The products that have resulted are treated herein in chronological order of development as much as possible. Inasmuch as most of these products are bonded together with adhesives, the major types of wood-bonding adhesives are also treated briefly.

1.1. Adhesives for Wood

The following list includes most of the adhesives which can be or have been used in wood and wood composite bonding applications.

- Natural adhesives
  - starch
  - soy flour
  - blood
  - casein
  - hide/bone
- Synthetic adhesives
  - urea– formaldehyde
  - melamine–formaldehyde
  - phenol–formaldehyde
  - resorcinol–formaldehyde
  - isocyanate/urethanes
  - poly(vinyl acetate) (PVA)
  - contact adhesives
  - epoxy resins
  - hot-melt adhesives

In the natural adhesive group, only limited quantities are still used today, largely in conjunction with a synthetic adhesive where the purpose of the mixture is to improve some characteristic of the adhesive. In early plywood hot-pressing applications, blood and starch or soy flour were used. Casein, a milk-based product, was a long-time favorite adhesive for cold-pressed plywood and lumber laminates. Soy flour glues were used in the early years of cold-pressed softwood plywood. Hide and bone glues constituted the original version of the hot-melt glue and were widely used as assembly glues in furniture construction. A disadvantage of the natural glues was that they were suitable only for interior uses, where exposure to liquid water would not be encountered. Casein and blood-soya glues were the most water-resistant, but neither could be classed as truly suitable for exterior exposure.

Synthetic adhesives have resulted from developments in the field of organic chemistry. Virtually all are obtained from petroleum, natural gas, or coal by-products.

Formaldehyde, HCHO, is a primary and necessary constituent of the first five synthetic adhesives in the listing. It is a simple organic chemical first identified during the latter half of the 1800s. Its irritating and toxic odor and preservative properties were known from the time of its early development. It is a ubiquitous chemical, formed naturally in small quantities by every process of incomplete combustion as well as in normal biologic processes. The human body has a natural formaldehyde level of about 3 μg/g, ie, 3 parts per million (ppm) in the blood at all times.

During the late 1970s, concerns were raised about levels of airborne formaldehyde in buildings resulting primarily from construction using composite panels bonded with urea–formaldehyde resins and combined with energy-efficient building practices which reduced air losses.

In an effort to address these concerns, regulations and guidelines were established. The U.S. Department of Housing and Urban Development (HUD) regulation 24CFR 3280.208, *Manufactured Home Construction and Safety Standard*, promulgated in 1985 (1), required emissions of 0.2 μL/L (ppm) or less from hardwood plywood and 0.3 μL/L (ppm) or less from particleboards, when both products are made with urea–formaldehyde adhesives and ultimately used in manufactured homes. The industries implemented voluntary standards, and formaldehyde emission levels were significantly reduced. In 1993, the National Particleboard Association voluntarily reduced emissions to 0.2 μL/L (ppm) or less for particleboards used in flooring applications. Airborne formaldehyde levels in most studies of conventional homes have shown average levels of less than 0.1 μL/L (ppm), a level which also is generally accepted by the U.S. Environmental Protection Agency as a level of concern. It should be noted that the average person cannot detect formaldehyde in air below levels of about 0.5 μL/L (ppm), although there have been reports of hypersensitive individuals. Another factor which should ease concern about formaldehyde is that most emissions occur as a result of formaldehyde trapped in the product during manufacture. As the formaldehyde is slowly released over time the natural emission rates decrease, resulting over time in decreasing levels in the surrounding air. Today there should be little concern for irritation problems from formaldehyde in most current construction and there should be no concern about cancer caused by breathing formaldehyde in normal air.

Phenol–formaldehyde (PF) was the first of the synthetic adhesives developed. By combining phenol with formaldehyde, which has exceptional cross-linking abilities with many chemicals and materials, and a small amount of sodium hydroxide, a resin was obtained. The first resins solidified as they cooled, and it was discovered that if it was ground to a powder with a small amount of additional formaldehyde and the application of more heat, the mixture would liquify and then convert to a permanently hard material. Upon combination of the powdered resin mixture with a filler material such as wood flour, the result then being placed in a mold and pressed under heat and pressure, a hard, durable, black plastic material was found to result. For many years these resulting products were called Bakelite, the trade name of the inventor. Bakelite products are still produced today, but this use accounts for only a small portion of the PF resins used.

Subsequently it was discovered that liquid PF resins could be produced and used as binders for other products. The primary uses for one class of PF resins is in foundry applications where the resin is employed in binding the sands used in the molds. The resin burns away during the molding process, allowing removal and recycling of the sand. Today the major use of PF resins is in bonded wood products, ie, plywood, hardboard, hardboard siding, oriented strandboard, and waferboard. PF resins produce strong, durable, and waterproof bonds; primary characteristics required in any product which may be exposed to the weather or to liquid water for significant time periods. PF resins generally produce a dark-colored glueline, require hot-pressing to cure, and are much more expensive than the popular urea-based adhesives used for interior exposures.

Urea–formaldehyde (UF) was also developed as an early synthetic adhesive by combining the two chemicals under carefully controlled heating (cooking) conditions. Small amounts of other chemicals are added to obtain other desired characteristics in the resin adhesives. Urea–formaldehyde resins are inexpensive, fast-bonding, produce a colorless glueline, are water-resistant, and tolerate a fairly wide range of bonding conditions. These resins are an almost ideal interior-grade adhesive, with the single exception of formaldehyde emissions. However, developments in improved resin chemistry have reduced potential emissions to unnoticeable levels, with a possible exception occurring in the case of a few hypersensitive individuals. Urea–formaldehyde resins cure at acid conditions which means that they can cure at room temperature with the simple addition of a small amount of acid catalyst, or more quickly under heat and pressure using the natural acidity of the wood as a catalyst.

Both melamine–formaldehyde (MF) and resorcinol–formaldehyde (RF) followed the earlier developments of phenol–, and urea–formaldehyde. Melamine has a more complex structure than urea and is also more expensive. Melamine-base resins require heat to cure, produce colorless gluelines, and are much more water-resistant than urea resins but still are not quite waterproof. Because of melamine's similarity to urea, it is often used in fairly small amounts with urea to produce melamine–urea–formaldehyde (MUF) resins. Thus, the improved characteristics of melamine can be combined with the economy of urea to provide an improved adhesive at a moderate increase in cost. The improvement is roughly proportional to the amount of melamine used; the range of addition may be from 5 to 35%, with 5–10% most common.

Resorcinol is to phenol as melamine is to urea. Resorcinol–formaldehyde (RF) is very expensive, produces dark and waterproof gluelines, but will cure at room temperature. As with melamine and urea, resorcinol is often combined with phenol to produce phenol–resorcinol–formaldehyde (PRF) adhesives, thus producing an excellent adhesive with some of the economy of phenol. These adhesives are the mainstay of the laminated timber industry which generally requires a room-temperature cure with durable, waterproof gluelines.

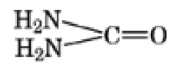
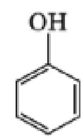
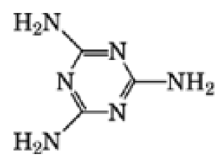
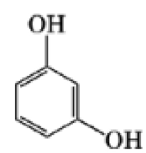
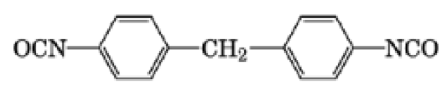
Another class of adhesives has been gaining more widespread use in the wood laminates and composites industries. These adhesives are isocyanates, the common name of a chemical group of diphenylmethane-*p,p*-diisocyanate polymers. They are excellent adhesives, fast-curing, and will produce durable, waterproof bonds if used in sufficient quantity. Considerations which have slowed wider usage of isocyanates are high cost (about $6\times$ urea resins and $3\times$ phenol resins); adhesive qualities which bonds to press plates as easily as to wood, thus requiring a totally reliable press release additive system; and finally, their toxic characteristics require a high level of manufacturing safeguards. The liquid adhesive should not contact the skin, and whereas only very minor amounts of odorless emissions occur during application and curing, about 4% of exposed persons are sensitive to these fumes and may develop a life-threatening asthmatic condition on continued exposure. However, their fast curing rate offsets some of the higher cost as compared to phenolics, and the other primary concerns can be handled by special care in monitoring, handling, and dust/ventilation controls. Provided they are used properly and safely, isocyanates have been found to be excellent bonding agents.

Four other groups of synthetic adhesives find uses in secondary processing, ie, overlaying, assembly gluing, etc, and in furniture and cabinet manufacture. Poly(vinyl acetate) (PVA) adhesives are widely used in application of veneers and other overlays to panel substrates and in some unit-assembly operations. PVA adhesives are an emulsion of polyvinyl acetate in water and cure by loss of water. The PVA adhesives are somewhat expensive, but are extremely versatile, cure at room temperature, and provide a colorless glueline. The curing reaction time may be decreased by addition of mild heat, or by using a catalyst in the case of special types of PVA resins. Table 1 lists the chemical formulas of all of the preceding chemicals widely used in wood-bonding applications.

Another widely used overlay adhesive is the contact type. These specialized adhesives, in the same group as rubber cement, may be of the solvent-base or water-base types. They are often used to bond overlays such as wood veneer, vinyl (poly(vinyl chloride)) films, or high pressure laminates such as countertop overlays.

Epoxy resins are also used in special applications, such as an overlaying procedure requiring a durable, heat-resistant bond of a difficult-to-bond overlay on a wood-base panel substrate. Metal sheets used as overlays, for example, often require an epoxy adhesive.

Table 1. Chemical Structures of Constituents of Principal Wood Adhesives

Name	Chemical formula	Chemical structure
formaldehyde	(HCHO)	
urea	(H_2NCONH_2)	
phenol	(C_6H_5OH)	
melamine	($C_3H_6N_6$)	
resorcinol	(1,3-$(HO)_2C_6H_4$)	
isocyanate	($(NCO)_2CH_2(C_6H_4)_2$)	
poly(vinyl acetate)	($(CH_3CO_2CH{=}CH_2)_n$)	

Finally, a large variety of hot-melt or thermoplastic adhesives have been developed in recent years. These are solid at normal temperatures, but melt and flow if heated and resolidify when cooled. A wide range of melting points and bond strengths are available, depending on the requirements of the application. These adhesives are widely used in furniture and cabinet construction and have largely replaced the hide/bone glues formerly used in these applications.

Assuming correct adhesive application and bonding conditions, it is generally agreed that the bonding mechanisms are the result of forces of molecular attraction between the adhesive and the wood surfaces. Any normal structural wood adhesive should be capable of producing bonds which are stronger than the shear strength of the wood. Treatments of the manufacture and uses of the various composite and laminated products given herein provide more specific details on the applications and uses of adhesives.

2. Manufacturing Processes

2.1. Safety

An extremely important safety issue with respect to all wood product manufacturing processes is personal worker safety. All of the processes use much moving machinery, usually including many saws or knives. Workers must continually remember the inherent dangers these machines involve as well as other possible dangerous situations which could result from malfunctions or other errors. In addition, most processes are more or less dusty and noisy. Most employers require use of safety glasses and many require hearing protection, safety shoes, and hardhats as well as other kinds of protection needed for specific jobs.

3. Plywood

Plywood is a panel made from wood veneers (thin slices or sheets) bonded to one another. Generally each ply is oriented at right angles to the adjacent ply, and the two face plies should have the grain direction parallel to each other. Thus most plywood will have an uneven number of plies, such as 3, 5, 7, or more. An exception to this is a four-ply construction in which the two core plies are oriented parallel to one another and perpendicular to the two face plies.

Plywood has essentially equal stability in both panel directions and is almost as stable as the parent wood in the direction of the wood grain. Strength properties in bending are roughly proportional in each panel direction to the amount of wood in those layers closest to the surface which are parallel to the wood grain direction. Thus as the number of plies increases, these bending properties become more equalized in both panel directions.

3.1. Hardwood Plywood

Hardwood is generally considered to be that coming from a tree having distinct leaves as opposed to needles, and usually but not always deciduous, ie, growing and losing a set of leaves each year. Whereas examples of small wood veneers bonded to other woods have been found in ancient tombs and other historical locations, wide usage of hardwood plywood did not occur until slicing and peeling equipment became available to produce veneers in reasonably sufficient quantities.

3.1.1. Hardwood Plywood Processing and Products

Production of hardwood plywood follows one of two general processes. These are illustrated in Figures 1 and 2. High quality face veneers are almost always sliced from halved or quartered logs in order to obtain the maximum quantity of highly figured veneer. These veneers are extremely thin, in the 0.4–0.7-mm thickness range. Some of the principal species used for decorative veneers are walnut, maple, birch, oak, as well as many tropical species, including teak and rosewood.

Hardwood plywood logs are almost always soaked or steamed to soften the wood, making it more amenable to slicing or peeling. If the logs are to be sliced, they are usually sawn into halves or quarter sections. These are called flitches. The slicer uses a long knife to move and slice across the flitch, producing a thin strip of veneer. The knife then retracts and the flitch is indexed forward by the desired veneer thickness and sliced

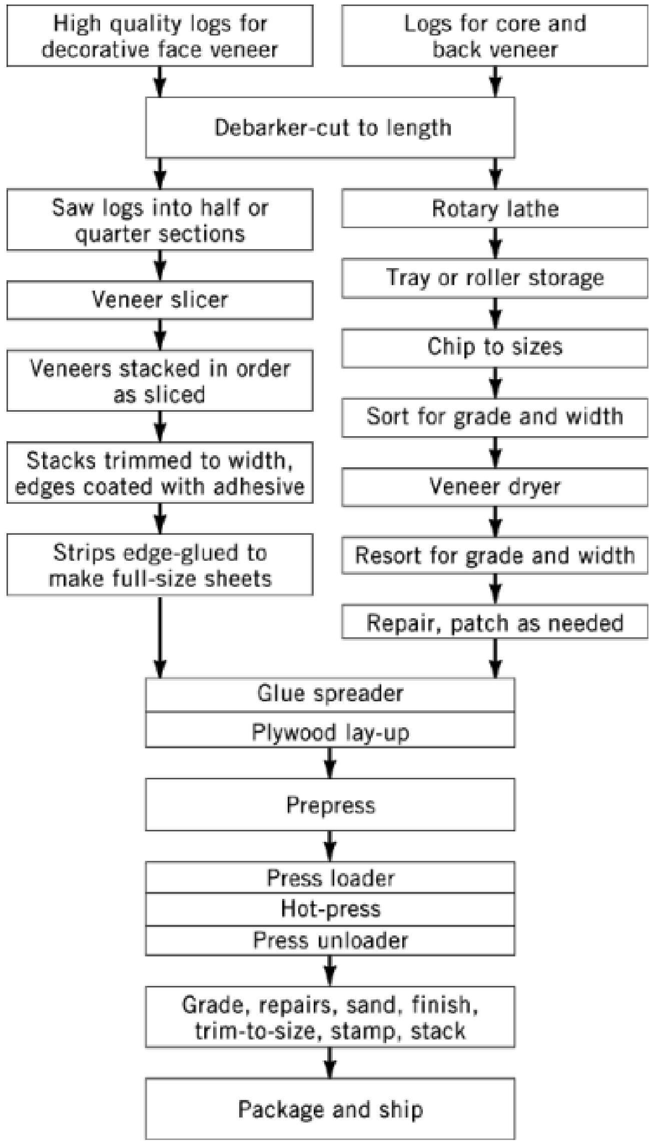


Fig. 1. The hardwood plywood process using sliced decorative veneers.

again. This cycle is repeated until no more veneer can be produced from the flitch. Veneers from each flitch remain together during the entire process so that wood grain patterns can be matched in the final panels.

Other veneers for backs and cores, or in the case of the tropical luauns, are almost always peeled on a rotary lathe. In this process, the log is rotated against a long, stationary knife and the log is essentially "unrolled" in a long, thin sheet. These sheets are called rotary-cut veneers.

Decorative veneers from the slicer are carefully passed through a long tunnel dryer. As they emerge from the dryer at 3–5% moisture content (MC), they are carefully restacked in the order they emerge. They proceed to a trimmer, which trims the stack to obtain parallel edges, at the maximum obtainable width. A coating of

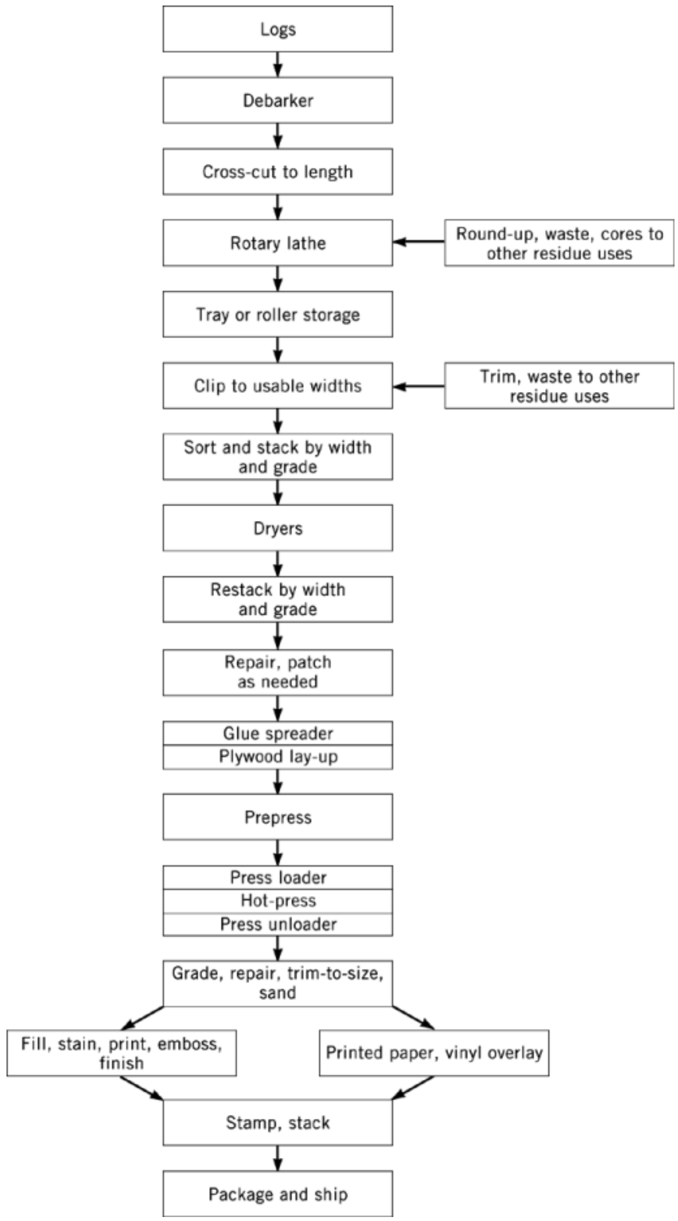


Fig. 2. The hardwood plywood process using rotary-cut veneers.

adhesive, usually a contact adhesive, is applied to the edges of the stack. Then the pieces are passed edge-to-edge through an edge-gluer, from which sheets of increasing width result with each pass through the machine. When the desired width, usually about 1270 mm, is achieved, the sheets are carefully stacked and moved to the panel lay-up area.

Veneers from the rotary lathe pass through a high speed clipper or knife which cuts out the usable widths, the objective being to obtain as many full-width sheets as possible. These veneers move along a table where they are sorted into piles by width and appearance grade. These piles of veneer are then fed sheetwise into long tunnel dryers. The veneers should be at 3–5% MC as they emerge from the dryers. Moisture sensors are used to check each piece, moisture control being an extremely critical part of the process. Veneers which are too wet are marked and placed in stacks to be redried. Veneers are again sorted after emerging from the dryer, special attention being given to grade and to those veneers in need of repair or patching. Because these are not face veneers, patching and repairs are limited to those required to allow the veneer to reenter the desired grade. This may involve simple taping of splits and tears or plugging of an oversize knot area with a wood plug. In the case of the latter, patches or plugs of various shapes are punched from strips of veneer. Then the plugging machine punches out a section of similar shape around the knot or defect and replaces it with a veneer plug of the same shape. Common shapes are boat, dogbones, and ovals.

The stacks of veneer are moved to the panel lay-up area, where adhesive is applied and veneers assembled into lay-ups ready to be pressed. Because core cross-veneers are only half-panel width, these stacks are cut into halves.

The primary adhesive used in hardwood plywood is urea–formaldehyde (UF) mixed with wheat flour as an extender to improve spreadability, reduce penetration, and provide dry-out resistance. A catalyst may also be added to UF resins to speed the cure or to cause the UF to cure. Scavengers also may be added to reduce formaldehyde emissions from finished panels. If more water-resistance is required using a UF bond, small amounts of melamine may be added, producing a melamine–urea–formaldehyde (MUF) adhesive.

For exterior applications, where water exposure is expected, phenol–formaldehyde (PF) or phenol–resorcinol–formaldehyde (PRF) adhesives are used. Only small quantities of this type of hardwood plywood are made, primarily for marine use.

Lay-up proceeds by laying down the veneer which is to be the back surface of the panel. Then a sufficient number of pieces of core veneer are passed through the glue spreader to form the next layer of cross-oriented veneer. The glue spreader commonly used in hardwood plywood manufacture is a roll coater in which a pair of opposing rubber rolls are coated with a thin layer of adhesive. As the veneer is passed between the rolls, the adhesive is transferred to the surfaces of the veneer. Adhesive is applied only to the cross-plies and in sufficient quantity to provide a continuous layer on both opposing faces of veneer. Thus, in the case of a three-ply panel, only the core layer is spread with adhesive and in that of a five-ply panel, the second and fourth layers both of which are cross-plies, are spread with adhesive. Then the top surface veneer, which is normally the decorative surface, is placed on the assembly.

As succeeding panels are laid-up, a stack of panels is formed. If the panels are to be cold-pressed, an uncommon procedure in modern manufacturing, the stack will be high enough to fit into the cold-press. The stack is rolled into the press, the press is closed under hydraulic pressure and the bonding pressure, 1035–1205 (ca 150–175 psi) is maintained for the time required to form a bond. This time could vary from 30 to 120 minutes, depending on temperature and the adhesive formulation used.

If the laid-up panels are to be hot-pressed and, for example the hot-press has 20 openings or spaces in which to place veneer assemblies to be pressed, the stack would be 20 panels high. If, as in the case of thin panels, two assemblies were to be pressed in each opening, the stack would be 40 panels high. The stacks are moved to a large one-opening pre-press where they are cold-pressed as a unit for several minutes. This pressing completes the transfer of adhesive from the coated faces to the uncoated faces and also provides a small amount of bonding so that the individual panels have sufficient integrity to be moved individually into the desired press opening.

After prepressing, the stacks move to the press loader. The press loader raises the stack vertically beside the press. As the top panel reaches each opening, the panel is manually pushed into the press. When the loader reaches the top opening of the press and all panels are in the press, the press begins the pressing cycle, closing on each panel and pressing the entire group of panels at 1035–1205 kPa (ca 150–175 psi) for several minutes at a temperature of about 140°C. Time in the press is proportional to the thickness of the panel(s) in each opening. Heating greatly accelerates the cure of the adhesive. The combination of heat, pressure, and moisture also produces a small amount of densification in the veneers, resulting in a finished panel density which may be a few percent higher than that of the original wood.

After the allotted pressing/heating time, the pressure is released and the press moves to the open position. By this time, the loader is again ready and as each veneer assembly is moved into its respective opening, the pressed panels are pushed out into the unloader on the opposite side of the press. As the press begins the next cycle, the unloader moves to deposit the pressload of panels into a stack.

The stacks are moved and again separated into individual panels where they pass a grading station. Those panels requiring touch-up or repair move to the repair stations. Panels then move to the trim saws where edges are trimmed to the final desired size, normally 1220×2440 mm (4×8 ft.). Panels are then touch-sanded to final thickness, and pre-finished as desired. Those panels with high quality decorative veneer faces are usually filled, stained to the desired tone, and finished with a clear finish.

Panels of the luaun type are mostly manufactured in the Far East by a similar process, but using rotary-cut veneers, and are then imported into the United States as raw panels. These panels usually begin their processing at a touch sander and then move to the desired finishing sequence where filling, coating, grain embossing, and final finishing steps occur. The panels may also receive a thin vinyl overlay or printed paper, followed by a clear finish. Many of these coated or overlaid panels are virtually indistinguishable from natural wood. After the finishing process, the panels are graded, defective panels removed, and the remainder packaged for shipment.

3.1.2. Uses and Treatments of Hardwood Plywood

Most early applications of hardwood plywood were those where the hardwood plywood was better adapted to the use than solid wood. One of the most important early uses was in curved or formed parts, an application particularly suited to the use of veneers which could be molded into intricate shapes during the pressing and bonding process. Then, as furniture manufacturers realized the inherently superior stability of plywood compared to solid wood, lumber-core or plywood panels began to be used for most flat-panel constructions in furniture.

Lumber core is a five-ply panel, usually about 19 mm (3/4 in.) thick, in which the bulk of the thickness, about 16 mm (5/8 in.) is edge-glued lumber. Yellow poplar and red gum are desired species for lumber core. Cross-plies of lower value wood veneers are laid at right angles to the core grain direction, followed by two thin surface plies of the decorative face veneer in a parallel direction to the core. This assembly is pressed and bonded to form a panel of exceptional quality, provided all steps are accomplished in a desirable manner.

Plywood furniture core panels, also about 19 mm (3/4 in.) thick, were normally made of a number of layers of relatively thick, 1.5–3.0 mm (1/16–1/8 in.) lower value wood veneers combined with thin surface plies of the decorative veneer. These assemblies were laid-up from glued veneers and then pressed while the bonding occurred. Both lumber core and plywood core have been almost totally displaced in recent years by particleboard or medium-density fiberboard, both discussed herein. This change resulted from the increasing availability and improved finishing characteristics of composites and from decreasing supplies of core lumber or veneer of suitable quality.

One type of thick hardwood plywood still available is imported from the northern Scandinavian countries and is generally known as Finnish birch. Characteristically, these plywoods are manufactured using multiple layers of veneer of the same thickness, about 1.5 mm (1/16 in.), and bonded with a urea–formaldehyde or melamine–urea–formaldehyde adhesive.

Thin hardwood plywood in the range of 4.5–6.0 mm (3/16–1/4 in.) was normally a three-ply construction with a thin, medium-quality back ply, a thicker lower value core, and another thin, high quality decorative face veneer. These panels were used as wall paneling, door facings, or for furniture/cabinet applications requiring thin panels. Currently, only relatively small quantities of these types of panels are produced in the United States. The majority of thin paneling used today is imported from the Far East and is made from various tropical species of the luaun group, sometimes known as Philippine mahogany. These panels are normally finished using one of the processes intended to create the appearance and grain pattern of a decorative veneer or other patterns.

3.1.3. Economic Aspects

The hardwood and decorative plywood industry has decreased in size and production significantly in the past few years. In 1994, there were an estimated 100 mills operating in the United States having a production volume of 1.135×10^6 m^3 (2). The dollar value of this production is extremely difficult to estimate because of the very wide range of prices for the products.

3.1.4. Specifications, Standards, Quality Control, and Health and Safety

The Hardwood Plywood and Veneer Association (HPVA) represents the manufacturers and associated industries in matters relating to specifications, standards, quality control, and health and safety factors. Specifications and standards for hardwood plywood products are found in the American National Standard Institute (ANSI) standard for *Hardwood and Decorative Plywood* (3). The most important product quality test procedures are bond quality tests and the formaldehyde emission test. The formaldehyde emission test is described in ASTM E1333-90 (4). Test panels are placed in a test chamber maintained at 25°C, 50% relative humidity (rh), 0.5 air change per hour, and having a test product loading rate of 0.95 m^2 of product surface/m^3 of chamber volume, ie, 0.95 m^2/m^3. These are considered to be normal conditions of temperature, rh, air ventilation rate, and product usage within a manufactured home. Formaldehyde concentrations within the test chamber must be ≤ 0.20 $\mu L/L$ (ppm) to qualify the material for use in manufactured homes. At the time of this writing (ca 1997), there is no emission regulation for products used in other buildings, but the majority of products are now manufactured to pass this stringent emissions test. Another important test is the flamespread test, described in ASTM E-84 (5). This test is designed to measure the potential of a product to ignite and contribute to the spread of a flamefront in a fire.

3.2. SOFTWOOD PLYWOOD

Softwood is generally considered to be that coming from a coniferous tree, ie, an evergreen tree having needle-like or scale-like leaves. There are exceptions to the evergreen rule, however. In addition, many hardwoods also may now be used in softwood plywood as core veneers.

3.2.1. Softwood Plywood Processing and Products

The first softwood plywood was made in 1905 using Douglas fir veneer, soya flour adhesive, and cold-press system. Figure 3 illustrates the traditional softwood plywood process. Veneer logs are kept wet until cut to peeler block lengths, about 2500 mm (100 in.). The peeler block may be stored in cold or hot water, or placed in large, steam-heated rooms until it is removed to be used for veneer. The block is placed in a charger, which quickly loads and positions the block into the lathe after the previous block is finished. The charger electronically scans each block and determines a point at each end of the log which will be centered in the lathe and will allow the optimum yield of veneer from the block.

After the block is chucked in the lathe, the lathe turns the block against the knife and peels the veneer in a continuous sheet as the knife moves toward the center of the block. When the knife cannot advance further without moving into the metal chucks, the lathe is stopped, the core of the block is dropped, the lathe is recharged, and the cycle repeated.

As the veneer leaves the lathe, it moves into a series of trays, long storage conveyors which provide short-term storage while the veneer moves through the clipper. The clipper is a high speed knife which chops the veneer into sheets which will maximize the yield of usable veneer. Unusable veneer is chopped into chips for use in paper or composites. The veneer sheets move along another long conveyer table where they are pulled

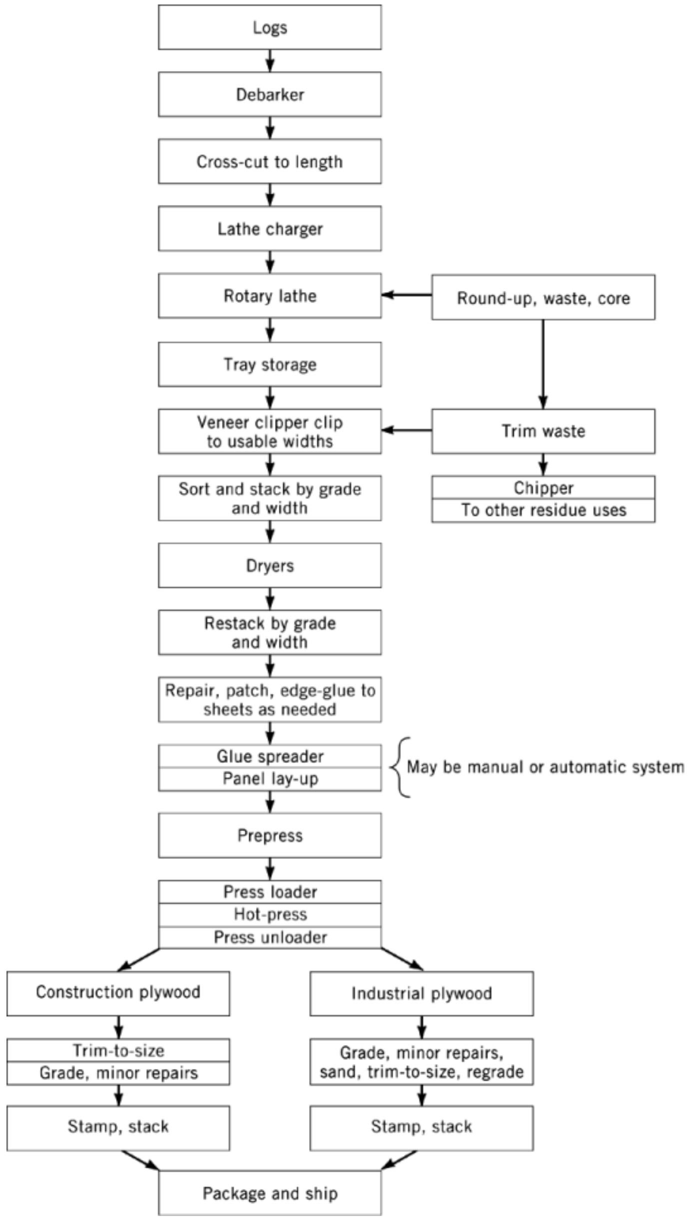


Fig. 3. The softwood plywood process.

and sorted into stacks by grade and width. The stacked veneer is moved to the dryer area where the sheets are placed end-to-end and moved through the long conveyor dryer. Hot air heated by steam, oil, or gas is blown onto the surfaces of the veneer to hasten the drying process. As the veneer emerges from the dryer at a desired moisture content (mc) of 3–5%, a moisture sensor marks those veneers which are not dry enough. These will be redried. The dry veneers are again sorted by grade and width and moved to the splicing and patching area. Here the narrow veneers are spliced together into full-size sheets. Some stacks of narrow veneers are cut in half, from 2550 mm (ca 8 ft.) to 1250 mm (ca 4 ft.) to make veneers for cross-plies. Some veneers are patched to make higher quality sheets for face veneers. The patching machines punch out defects such as large knots and refill the hole with a similarly sized piece of clear veneer. Then the stacks of veneer are moved to the gluing and lay-up area. Plywood manufacture is a labor-intensive operation. No other wood-base composite manufacturing operation requires as much hand labor, which is excellent from the viewpoint of providing jobs, but contributes significantly to the final cost of the end-product.

The adhesive used in virtually all softwood plywood has a phenol–formaldehyde (PF) base to provide an exterior-grade, durable, waterproof bond. Thus, most grades of plywood can be used in structural applications. A very small percentage of softwood plywood is made using interior-grade adhesive systems, and this material is used in interior cabinetry, furniture, and shelving.

A typical glue mix for exterior plywood is:

Component	Percentage (by weight)
water	14.65
furafil extender	5.03
wheat flour	3.02
50% caustic soda (NaOH) solution	1.51
diesel oil (defoamer)	0.30
phenol–formaldehyde resin	75.49
	100.00

A typical glue mix for interior plywood is:

Component	Percentage (by weight)
water	69.33
powdered blood–soya mix	15.61
lime (CaO) powder	4.13
50% caustic soda (NaOH) solution	2.39
silicate of soda solution	5.33
phenol–formaldehyde resin	3.21
	100.00

There are two types of gluing and lay-up areas, manual and automated. The manual system is similar to that used in hardwood plywood; surface veneers are laid down and core veneers are passed through a roll spreader where adhesive is applied to both sides. Again, every other core layer is spread with adhesive. Adhesive spreads for western softwoods are usually in the range of 0.88–1.02 kg/m^2 of double glue line (amount of liquid adhesive on both sides of veneer). In the case of Southern pine or hardwood veneers, glue spreads are increased to the range of 1.36–1.52 kg/m^2 of double glue line.

In the automated lay-up system, each layer of veneer (with exception of the top surface veneer) passes under an automatic adhesive application system. This may be a spray application, a curtain coater, or an extruder, each of which is designed to apply a uniform adhesive spread on the upper face of each veneer. After all except the top veneer have been spread with adhesive and laid together, the top veneer is added. The mc of the veneer–adhesive assembly at this point should be about 8%.

The assembled veneers for each panel are placed in stacks equivalent to the number of panels to be pressed in each pressload. Each stack is then placed in a cold single-opening prepress and pressed for a short time to assure transfer of adhesive from the spread faces to the unspread faces. This pressing also provides a small amount of wet adhesion between veneers and facilitates handling of the panels as they are moved into the hot-press. The stacks of panels are moved to a lift on the side of the press. The lift raises the stack and the top panel is pushed into succeeding panel holders on the press loader as the stack passes each holder. The press opens after completion of pressing and curing the adhesive on the current pressload. The press loader then moves the raw panels into the spaces between the hot-press platens. As each raw panel moves into the press, it pushes the newly pressed panel out into an adjacent holder on the press unloader. The press closes and presses the new load for a time sufficient to cure the adhesive. Temperatures are usually about 140°C and presstimes are in the range of 3.75–4.25 min for 12.7 mm (1/2 in.) thick panels. Pressing also results in a slight compression of the veneer, which results in a panel of slightly higher density than the original wood density. Pressed panels move from the unloader into stacks which are set aside to cool for 4–12 h.

There is a hybrid product available which has a veneer back, a layer of PF-coated wood particles, core veneer cross-ply, another layer of wood particles, and a top veneer. This assembly is pressed into a panel, trimmed to size, and sold into the structural-use panel market where it competes with plywood and oriented strand board.

3.2.2. Secondary Treatments and Uses

Depending on grade, panels may receive from no processing to significant processing beyond this point. Structural sheathing panels, a nonappearance grade used as structural wall sheathing, roof sheathing or flooring, may be simply trimmed to size, grade-stamped, and packaged for shipment. Appearance-grade panels will have surface defects shimmed, patched, or filled. Then the panels will be sanded to a uniform thickness, trimmed to final dimension (usually about 1220×2440 mm (4×8 ft.), regraded, and packaged for shipment. Specialty panels may receive additional treatments, such as overlays for concrete form panels, shelving, sign materials, or other uses requiring improved surface properties. Panels for siding might be cut to resemble rough-cut lumber and grooved at intervals to show the appearance of board-on-board siding. Other treatments might include pressure-treatment with preservatives or fire-retardant chemicals for special applications requiring these characteristics.

3.2.3. Economic Aspects

The structural plywood industry now has (ca 1997) about 105 operating mills, representing a significant decrease over the past several years. Production in 1994 was about 17.4×10^6 m^3 (2), also representing a marked decrease over previous years. This decrease is a result of several factors, two of the most important being a decrease in availability of suitable veneer logs, especially in the western states, and competition from the newer oriented strand board structural panel industries.

3.2.4. Specifications, Standards, Quality Control, and Health and Safety Factors

APA–The Engineered Wood Association represents the softwood plywood and oriented strandboard industries in the areas of specification, standards, and quality control (QC). An APA product standard, PS1-95 (6), discusses the above areas in detail. The following listing summarizes plywood characteristics covered in PS1-95.

Classification—a review of exposure durability in terms of interior and exterior grades of plywood

Plywood requirements—includes wood species used, synthetic repair requirements, veneer grades, veneer layers and thicknesses, panel grades with respect to end-use, adhesive bond requirements, panel construction and workmanship, scarf and finger-jointed panels, dimensional tolerances, moisture content, and packaging and loading

Testing—includes test specimen preparation, bond durability tests, and structural performance tests. It should be noted that formaldehyde emission tests of phenolic bonded products such as structural plywood are not required because emissions are normally about 0.02–.03 μl/L (ppm), well below the previously noted safe level of 0.10 μL/L (ppm).

Grademarking and certification—includes certification procedures performed by a qualified inspection and testing agency, and definitions of panel marking requirements

4. Insulation Board and Structural Fiberboards

4.1. Production, Processing and Shipment

4.1.1. Insulation Board

The panel products known as insulation board were the earliest commodity products made from fibers or particles in the composite panel area. These are fiber-base products with a density less than 500 kg/m^3. Early U.S. patents were obtained in 1915 and production began soon thereafter. The initial production used wood fiber as a raw material, but later products were made of recycled paper, bagasse (sugar cane residue), and straw. Schematics of the two major processes still in use are shown in Figure 4.

In the process using wood residues, the raw material (usually wood chips) is passed through a chip washer to remove extraneous materials such as dirt, sand, stones, or metal. The washed chips move to a refiner where the chips pass between rotating steel disks with molded patterns in the faces of the disks. The disk faces are maintained at a small, controlled distance, 0.3–0.5 mm, which results in conversion of the chips into fiber and small fiber bundles as they pass between the disks. The fiber drops into a stock chest, where it is mixed with a large quantity of water. Large paddle mixers are used to keep the fiber in a uniform suspension. This fiber slurry is then moved to a smaller stock chest, where additives are metered into the slurry. Additives may be wax emulsion, starch or PF resin as binder, and alum. Alum is used to change the acidity (pH) of the slurry, which causes the PF resin to precipitate from solution and deposit onto the fiber. One process uses a linseed oil emulsion as a binder. Only small amounts of binder are required in these fiberboards because most bonding is the result of hydrogen bonding, similar to that used in paper-making.

The fiber slurry is pumped to the mat-forming box of a wet-process forming machine. This is a modification of the Fourdrinier machine, widely used in the paper industry. A wide endless wire screen belt, usually about 2540 mm (100 in.) wide, moves under the flow of fiber and water. The water drains through the fiber and through the belt to be recirculated back to the stock chest. The fibers are deposited on the belt at a rate consistent with the speed of the belt to produce a finished panel of the desired thickness and density. The belt then passes over a number of suction boxes, in which a partial vacuum is maintained. The air drawn through the fiber mat draws more water from the mat through the screen and through a series of holes in the top of the suction boxes, further consolidating the mat as well as removing excess moisture. It should be noted that this process uses large volumes of water. Whereas most of the water is recirculated, current regulations concerning clean water have hampered manufacturers, ensuring that in all probability no more of these plants will be built.

The formed mat is carried along on the wire screen and is trimmed to the desired width and length by high pressure water jets. The mats then pass onto another endless wire screen which carries the mats into a long heated drying chamber. The mat may contain 200–300% moisture based on the dry weight of the mat as it enters the dryer. Fans circulate hot air within the dryer, a procedure which removes the majority of the water from the fiber. Also, bonding occurs at points within the mat where individual fibers or fiber bundles touch one another. Some of the bonding is a result of hydrogen bonding at fiber-to-fiber interfaces and some bonding is a result of the presence of additives at these points. As the dry (5–7% mc) mat emerges from the dryer, it is already a useful product, having its own inherent properties and characteristics. These panels are quite low in density, 240–500 kg/m^3, and a relatively low strength, because primary uses concentrate on insulative

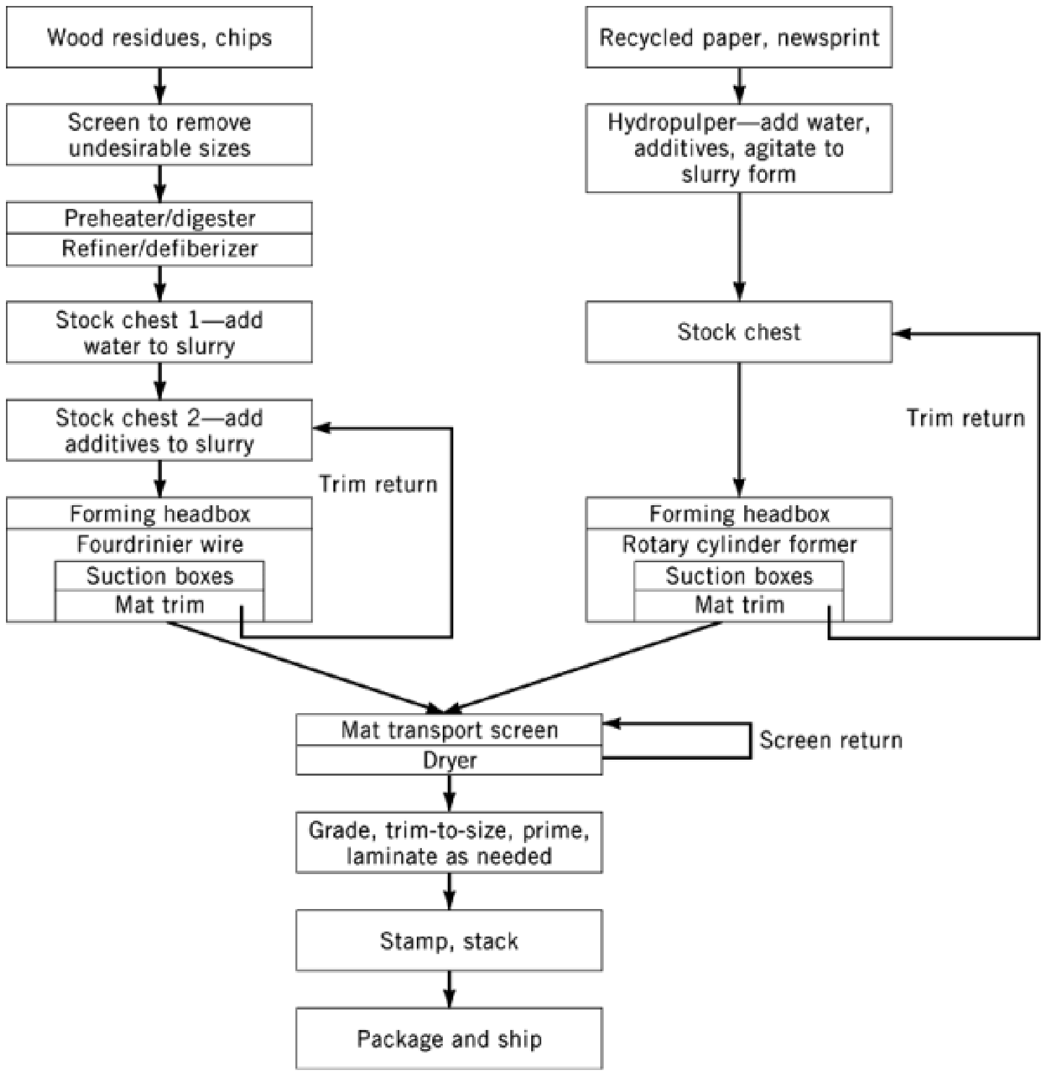


Fig. 4. Insulation board processes.

abilities and not on high strength. Processes using bagasse or straw are configured similarly to those using wood residues, with minor differences in the fiber preparation steps at the beginning of the process.

The processes using recycled paper fiber are also different at the beginning of the process. Mills using these processes are located near large cities, where large quantities of recyclable paper are available. Of interest in the context of the present emphasis on recycling is the fact that both of the mills producing these products have been operating for well over 50 years.

Paper is placed in a hydropulper, a large water tank equipped with a heavy motor-driven propeller at the bottom. The propeller agitates the water and wet paper and separates the paper fibers into a fiber slurry. Additives are added and mixed as needed at this point. This is a batch process and as such requires more than one hydropulper in order to be processing one tank as another is being emptied of slurry and refilled with water. The slurry is pumped into a box having a large-diameter cylinder covered by a wire screen rotating slowly within it. Fibers are deposited on the screen as water is pumped out of the screen and returned to the process. The fiber mat is carried up and over as the screen rotates and then transferred to a flat wire screen belt which moves the mat across suction boxes and onto the dryers.

4.1.2. Structural Insulation Boards

Structural insulation boards are made by a process similar to that used for insulation board, with the exception of another additive which provides additional weight, strength, and water resistance. The additive is normally asphalt, which is added in a pulverized form in the additive stock chest. As the asphalt is carried through the dryers on the fibers, the heat of the dryer melts the asphalt, which flows and coats the fibers. When the panels emerge from the dryer and cool, the asphalt hardens, providing added bonding, strength, and water-resistance properties.

4.2. Secondary Treatments and Uses

Insulation boards normally have few secondary treatments. Some boards may receive a coating of primer and others may be laminated into panels of several thicknesses. Insulation boards are used for economical, insulative wall paneling, ceiling tiles, bulletin boards, and similar uses. Laminated panels are used for insulative panels, usually as roof decking or insulation under built-up roofing.

Structural insulation boards are used primarily for wall sheathing in constructions where wall diaphragm racking resistance is provided by other means, such as structural panel corner bracing or metal strip bracing. Where allowed by building codes, these methods of construction do provide more economical construction.

4.3. Economic Aspects

In 1994 there were 8 operational insulation board producers in the United States. These mills produced about 1.15×10^6 m^3 (2). The number of mills and total production volume have also decreased in this industry, primarily as a result of changes in building codes and availability of other competitive sheathing products. Both wood composite panels and plastic foam sheathings have captured a segment of these markets.

4.4. Specifications, Standards, Quality Control, and Health and Safety Factors

Formerly, there was an Insulation Board Institute representing the insulation board industry, but the decline in the market and number of producers has led to its demise. Currently (ca 1997), the industry is represented by the American Hardboard Association (AHA). Specifications and standards are found in American National Standards Institute (ANSI) standard for *Cellulosic Fiberboard* (7). The standard includes descriptions of the various types and classes of fiberboard, as well as requirements for physical and dimensional stability properties. Quality control tests are limited to a few basic strength and stability tests, including bending strength, bond strength, and moisture resistance.

5. Hardboard and Hardboard Siding

5.1. Production, Processing, and Shipment

Hardboards and hardboard siding are fiber-base panel products having densities in the 500–1000-kg/m^3 range. Two density classes are made: medium density at 500–880 kg/m^3 and high density, $>$880 kg/m^3. Hardboards are generally thin products, 2.5–9.5 mm in thickness, whereas the siding products are usually 11.1–12.7 mm in thickness.

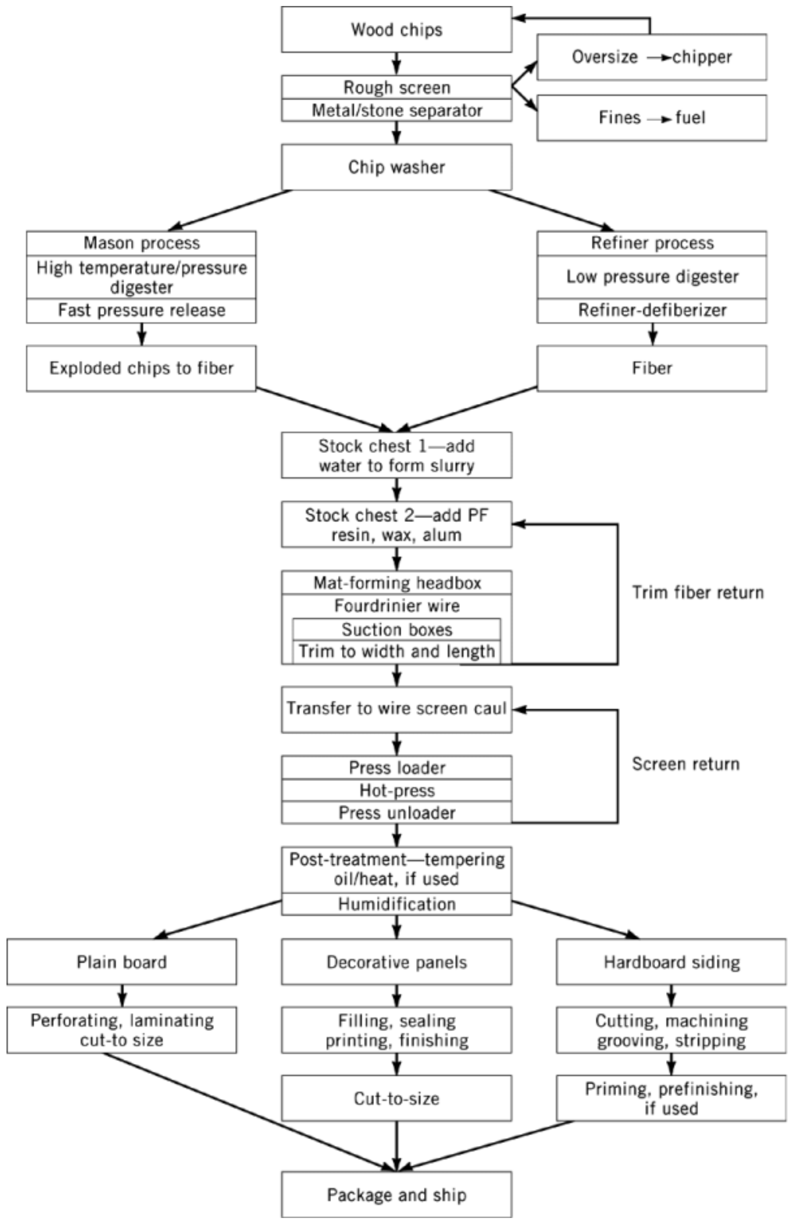


Fig. 5. The wet-process hardboard process.

The first industrial hardboard was developed by W. Mason in the mid-1920s; he found that a mat of wet fiber pressed in a hot press would produce a self-bonded flat panel with good strength, durability, and stability. The product was patented in 1928, trademarked as Masonite, and commercial production began. Over time several other processes for producing hardboards have been developed from modifications of the original process. Brief descriptions of these processes follow and a flow chart of the process is shown in Figure 5.

5.1.1. The Mason (Masonite) Process

In this system, wood chips are sealed in a small steel digestor and steamed at high pressure, ca 4.1 MPa (ca 600 psi) for about 1 min. A valve at the bottom of the digestor is then opened quickly and the sudden release of the pressure simultaneously defiberizes the chips and blows them out of the digestor. The fibers move in a slurry from a stock chest into a Fourdrinier-type mat-forming machine. The speed of the moving wire screen and amount of fiber deposited on the wire screen determine the final density and thickness of the product. The fiber mats pass across suction boxes to remove excess water and are then trimmed to width and length, a size controlled by the size of the hotpress, usually 1270 mm wide and 2490 or 4880 mm long. The mats are transferred from the Fourdrinier wire screen to another wire screen roughly the same size of the mat. This screen carries the mat through the pressing process, where it is removed and returned for another cycle through the process. The mats and screen move into a press loader. When the loader is full, the press opens, discharges the previous load, and the loader moves the next load of mats and screens into the press which maintains a temperature of 190–218°C.

The press closes and the initial pressure and heat force much of the water held in the fiber out of the mat and press as water or steam. The press continues to close until the target thickness and density of the product are reached. The press then maintains this position as the mats continue to absorb heat from the press. The heat converts the remaining water to steam as the temperature in the pressed mat rises above the boiling point of water, 100°C. The steam pressure forces steam through the wire screen under the mat and toward the edges of the press. In this manner the mat continues to dry, and two natural bonding processes take place. The majority of bonding is thought to result from softening and transferring of lignin under moist heat conditions and then drying on adjacent fiber surfaces as the mat dries in the press. The other bonding process is similar to that occurring in paper manufacturer, where adjacent, reactive hydroxyl, –OH, units bond to one another and other reactive sites during the drying process. To aid in removal of water and steam during pressing, it is a common practice to use a breathe cycle. This is done by quickly reducing the press pressure to the point where only a minimal pressure is exerted on the board. Steam escapes with a loud squeal as it passes between the board surface and the press platen surface. After a few seconds, the press is quickly returned to high pressure and remains at proper thickness position for the remainder of the press cycle. It is critical to insert the breathe cycle at the optimum point in the press cycle in order to remove as much moisture as possible in a short time period and then return the press to position before the resin binder cures. Then, when the pressed mats are dry and the press is opened, strong, stable, and durable panels are removed from the press without the requirement of added binder. The original Masonite process, used for many years, followed this procedure. It should be noted that both PF resin and wax were added in small amounts in later years to provide improvements in strength, stability, and durability. The Masonite process is an example of a wet–wet hardboard process; that is, the mat is formed wet and pressed wet.

5.1.2. Wet-Process Hardboard From Refined Fiber

This hardboard is another form of wet–wet hardboard. The principal difference between this process and the Masonite process lies in the method of preparing fiber and the additives used in the boards. Fiber is prepared by processing wood chips through a pressurized refiner. In this machine, chips are metered into a chamber under steam pressure at 520–830 kPa (75–120 psi). As the chips move slowly through the chamber, they are heated and softened by the steam. They then move from the pressurized cylinder (digestor) into the refiner, where they pass between serrated disks rotating at high speed and maintained in close proximity. One or both disks may rotate, depending on the design of the refiner, although most modern refiners use only one drive motor and rotating disk. The rubbing action between the disks separates the chips into fibers, which are actually bundles of fibers mixed with individual fibers. The fibers move out of the refiner into a stock chest, where they are mixed with water into a fiber slurry.

The slurry is pumped into another stock chest, where wax in emulsion form, usually about 0.5–1.0% wax-to-fiber weight, and 1–3% PF resin are added. PF resin is also added on the basis of resin solids-to-dry fiber. Then a small amount of alum is added, which changes the pH (acidity) of the slurry, causing the resin to precipitate from solution and deposit on the fibers. Resin is required in greater quantity than in the Masonite process because only light bonding occurs between fibers prepared in a refiner. The fiber slurry is then pumped to the headbox of a Fourdrinier mat former, and from this point the process is similar to the Masonite process.

5.1.3. Dry-Process Hardboard

Dry-process hardboard is produced by a dry–dry system where dry fiber is formed into mats, which are then pressed in a dry condition. A flow diagram of this process is shown in Figure 6. In this process, wood chips, sawdust, or other residues are refined to fiber in pressurized refiners. Wax and PF resin may be added in the refiner or immediately outside of the refiner, in the fiber-ejection tube or "blowline." It is also noted that a small amount of dry-process hardboard is made with UF resin binders. UF resins, because of their inherent faster curing at lower temperatures, can be added only at the blowline or in a blender located after the dryer.

As the fiber exits the refiner, it moves at high velocity and turbulence into and through the blowline. Blowlines may be 15–30 m (ca 50–100 ft.) in length and 100–150 mm (ca 4–6 in.) in diameter. During passage through the blowline, a sharp decrease in steam pressure occurs. This results in flash-off of moisture and a decrease in temperature of the fiber. Fiber is generally at only 30–40% mc as it exits the blowline. The blowline is an excellent point for addition of wax and resin to the fiber because of the extreme turbulence and mixing which can occur in the blowline. Generally, because little natural bonding occurs in this process, dry-process hardboard requires more wax and resin than wet-process hardboard. Usually 0.5–1.5% wax and 5–7% PF are used (9–11% UF, if used).

From the blowline, the fiber is blown into a tube dryer. Tube dryers are 760–1520 mm (30–60 in.) in diameter and up to 100 m or more in length. Air heated by steam heat exchangers or direct flame is blown through the dryers and moves the fibers in suspension as they dry and pass through the dryer. Temperatures are in the 120–150°C range at the inlet to the dryer and about 70°C at the dryer exit. Fiber moisture should be in the 6–12% range at this point if blowline blending is used. It must be lower if machine blending is to be used later because of water added with the adhesive resin. The resin will not cure in the dryer because of both the short residence time and the cooling effect of evaporating water in the dryer. Where there is moisture in the fiber, this drying and evaporating effect prevents the resin from becoming hot enough to cure.

From the tube dryer, fiber drops into a cyclone which separates the fiber from the moist, warm air. The fiber falls from the bottom of the cyclone into a large bin and in then moved to the mat forming line. If machine-blending of fiber with additives is used, it will occur at this point, immediately before the forming line.

Mat forming is usually accomplished by 2–5 similar machines in sequence, each depositing a portion of the fiber. A plastic or wire screen moves under each forming head, which results in a cloud of fiber falling onto the screen. Under the screen are suction boxes which aid in pulling the loose fiber toward the screen and providing a small amount of mat densification. Immediately past each forming head is a rotating toothed roll called a scalping roll. The scalping roll is adjusted to remove the uneven top of the mat so that the mat will be flat and uniform as it reaches the next forming head. Moisture control is extremely critical, so there will also be moisture-sensing devices situated along the former. These devices provide a measurement of the mat moisture content in order to ensure that moisture is in the proper range at this point and to alert operators of any need for adjustment of moisture. As the mat emerges from the last forming machine and scalper, it should contain enough fiber per unit area to produce the desired thickness and density of the final product. The mat may be 10–20 times thicker than the final board at this point and quite loose in composition. In order to make the mat more compact and to improve the handling capabilities of the mat as it moves toward the press, the mat now moves through a precompressor. This machine is a pair of opposing wide belts which gradually compress the

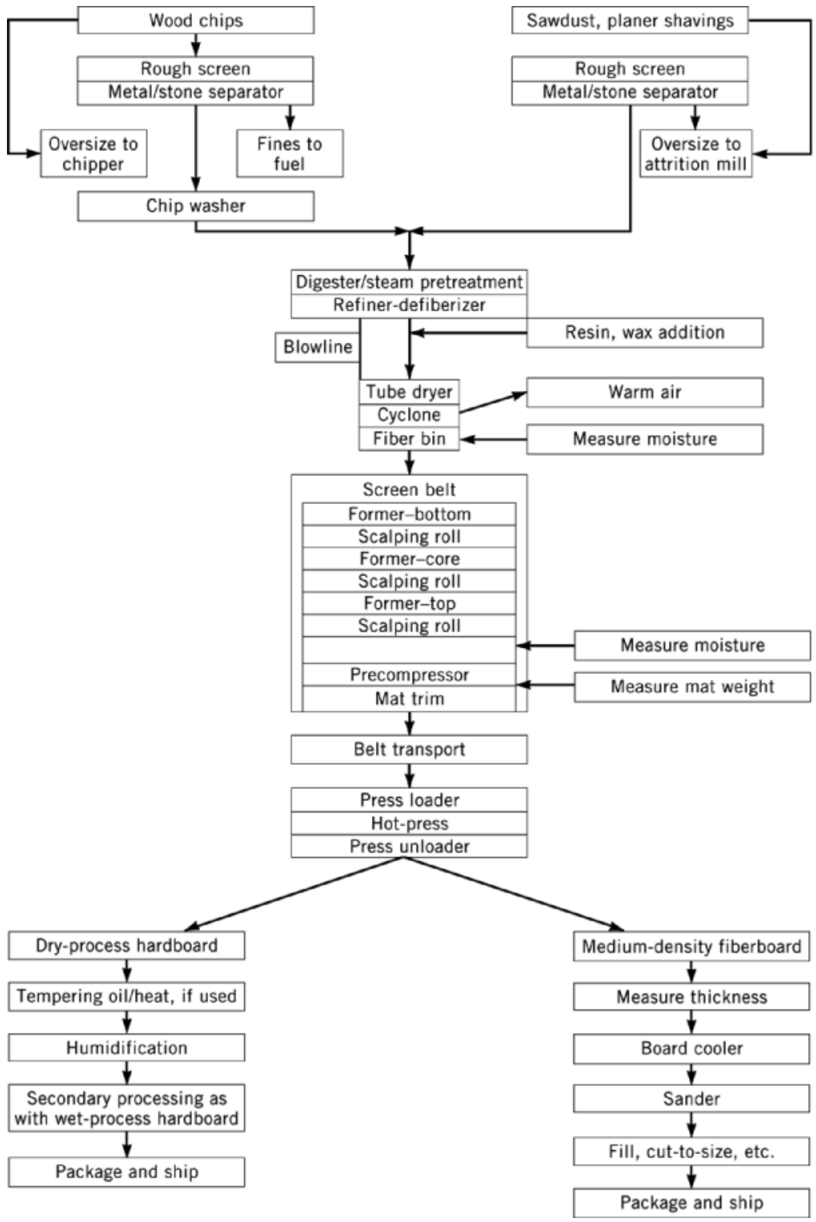


Fig. 6. The dry-process hardboard (and medium-density fiberboard) process.

mat to a minimum thickness as it moves between the belts. A thinner mat, 3–5 times the final board thickness, emerges from the precompressor. The mat is then trimmed to standard width and length and from this point is transported on wide belt sections. Usually, there is a device which continually measures the weight of fiber per unit area at this point to ensure that the desired mat weight and uniform cross-panel density are being formed. Mats which are off-weight or uneven in weight will be rejected at this point and the fiber returned to the system for recycling into other mats.

The mats are moved along the line to the press loader. When the loader is filled and the press opens to remove the load of freshly pressed boards, the loader pushes the new boards into the unloader and deposits the load of mats on the press platens. The press closes as quickly as possible to the desired panel thickness. More pressure, as much as 4.8–6.9 MPa (700–1000 psi) is required to press high density dry-process hardboard, because the dry fiber exhibits much more resistance to compression and densification than wet fiber. Press temperatures are also higher, in the range of 220–246°C. No screens are used in the dry-process, but the moisture in the mats requires a breathe cycle during pressing to avoid blowing the boards apart at the end of the cycle. Because no screens are used, the products are called smooth-two-sides (S-2-S), in contrast to the wet-process boards, which have a screen pattern embossed into the back side and are known as smooth-one-side (S-1-S).

5.1.4. Wet–Dry Hardboard

Wet–dry hardboards are a special class of boards in which the fiber is processed through the mat-forming stage in the same manner as in the case of wet-process board. However, an emulsion of a drying oil such as linseed oil is used as the binder and is applied in the stock chest preceding the former. Because this oil requires a long drying and cure time, the wet mats are passed into and through a conveyor dryer, as in the insulation board process. The mats are often sprayed on one surface with the emulsion immediately before the dryer. As the mats emerge from the dryer, every other mat is turned over so that the two oil-sprayed faces are adjacent. This assembly of two mats proceeds to the press loader and press, where it is pressed into one board. The drying oil completes the final cure and bonding action in the press. This process requires extremely high press temperatures, usually about 246°C, and great care must be taken to avoid press fires.

5.1.5. Dry–Wet Hardboard

Dry–wet hardboards are the other possible manufacturing alternative. Fiber is processed as in the dry process up through the mat-forming stage. PF binders are used in this system. Then, as the mats are ready to enter the press loader, a large quantity of water is sprayed onto the surface of the mat. This water saturates the top surface of the mat and is sufficient to raise the total moisture content of the mat to 20–40% mc, depending on the thickness and density of the product. Thinner, more dense products require more water. The press operates at about 200°C, and as the press closes on the mats, the water is heated to steam. The steam quickly heats and softens the mat, requiring less pressure to compress the mat and produces a hard, dense top surface much like a wet-process surface. However, because there is much less total water in the mat in this system compared to the wet-process system, press cycles are significantly shorter, which produces more product per unit of press surface per unit of time.

5.1.6. Hardboard Siding

Hardboard siding is, as the name implies, a hardboard intended for use as an exterior siding material for buildings. These products have been made using all of the previously outlined hardboard processes, using PF or drying oil binders. Two products, one of which is no longer made, used a powdered thermoplastic binder as the durable adhesive. All of these products were and are made to perform adequately as siding materials for the life of the buildings on which they are installed. A normal life cycle, assuming proper installation and finishing, is at least 25 yr.

Several additional facts are worthy of mention in regard to hardboard siding. The majority of the product is made in the medium-density range, between 640–880 kg/m^3; thicknesses are normally 11.1–12.7 mm. In addition to the normal smooth panels, there are many embossed surface patterns available which simulate rough sawn lumber siding as well as stucco, stone, brick, and shingle patterns. Embossed panels are made by attaching patterned steel plates to the press platens. A mirror-image of this pattern is then embossed into the top surface of the siding as it is being pressed. Almost all siding is preprimed and possibly prefinished before delivery to market. A variation of the siding product is also available as a roofing material which resembles a shingle or shake roof when installed.

Regardless of which of the various types of production processes hardboard panels follow, processing and shipment are generally quite similar for each kind of hardboard panel. Depending on the projected end-use of the panels, some will be tempered or heat-treated immediately after pressing. These treatments provide an added measure of resistance to water, or retard the rate at which the products will absorb water during exposure. The treatment is especially useful in the production of siding or roofing products. Tempering can be a two-stage operation, where the panels are passed through a bath of hot drying oils and then are placed in large racks and passed through a heated chamber. The chamber is heated to about 135°C, and products require 3–4 h to pass through the chamber. Some products may not receive the tempering oil dip, and will only receive the baking or heat treatment. Almost all hardboard products are humidified after pressing and heat treatment, if they are used. Humidification is necessary because the products emerge from the press and heat-treatment, if used, in an almost oven-dry condition and the moisture content of the panels needs to be increased to a level close to that expected in actual use, or about 6–10% mc. Humidification helps to avoid many swelling problems, ie, warping or buckling, which do occur if the panels are installed dry and then allowed to find their own equilibrium in use. The products are generally placed in large racks and passed through a large chamber maintained at high humidity and high temperature conditions.

After humidification, the products are trimmed to size and stacked. The stacks are then moved to the next processing step and many of the secondary treatments of hardboard will take place at the panel production site. These latter may include the following:

- For basic hardboard
  - packaging and shipment of raw panels
  - touch-sanding to close thickness tolerances
  - punching to produce perforated board (pegboard)
  - sealer coating
  - laminating to produce thick panels
  - decorative finishes such as wood grain or other decorative designs similar to those used in the hardwood plywood industry
  - cut-to-size for specific customer orders.
- For hardboard siding
  - sanding or planing to thickness
  - cutting or machining decorative groove patterns
  - cutting into strips for lap siding
  - cutting into shingle/shake patterns
  - sealing/priming with exterior-grade primer
  - prefinishing with exterior-grade topcoat

Upon completion of the various treatments the products may receive, the panels or strips are stacked, wrapped, labeled, and shipped.

5.2. Secondary Treatments and Uses

Because hardboard products are utilized in a myriad of different ways, the variety of secondary treatments used by customers are practically unlimited. Hardboards are used in furniture, cabinets, paneling, doors, toys, and a host of other uses. Post-treatments may include cutting-to-size, finishing treatments with roll-applied patterns, melamine overlays, printed paper overlays, paints, and even some extremely durable and water-resistant coatings used in tub and shower linings or other uses where water contact is frequent and extreme.

A separate mention is merited for a special molded hardboard product. These are made by a process in which either a fiber mat or hardboard panel is placed between two shaped platens and press-molded to a three-dimensional configuration. The most common resulting shape is a doorskin which resembles a wood panel door. The doorskins are bonded to wood frames to make an excellent, attractive, and relatively inexpensive door. This fiber/panel molding process is also used to make a wide variety of molded interior linings used in automobile manufacture.

5.3. Economic Aspects

In 1994, there were 16 operating hardboard and hardboard siding mills in the United States. Production was $1.535 \times m^3$ (2) in standard hardboard products. These figures do not include the significant quantities of door skin products made, for which production quantities are not tabulated. Production of hardboards has been relatively stable in recent years, considering them as a group. There have been a few new mill closings and a few mill start-ups. In addition, imports of hardboard have also become more common in recent years.

5.4. Specifications, Standards, Quality Control, and Health and Safety Factors

The hardboard industry is represented by the American Hardboard Association (AHA). Specifications and standards are contained in several ANSI standards (8–11). These standards define the various hardboard product categories as well as specific product qualities required for each group.

There are five classes of basic hardboard for which ANSI A135.4 (8) summarizes required performance levels of water resistance in terms of water absorption and thickness swelling, modulus of rupture (breaking strength), and tensile strength, both parallel and perpendicular to the surface. These test procedures are found in ASTM D1037-93 (12). For prefinished hardboard paneling, ANSI A135.5 (9) specifies qualifications which are primarily related to the surface finish. These are abrasion resistance, adhesion of finish, fade resistance, gloss, heat resistance, humidity resistance, scrape adhesion, and stain resistance. The AHA ANSI standard for medium-density fiberboard for interior use, ANSI A208.2 (10), has been superseded by the NPA standard for medium-density fiberboard, also ANSI A208.2 (13). This latter standard represents the small amount of hardboard made with UF resin binders which are specifically limited to interior uses, most of which falls into the medium-density group; this standard is discussed in detail herein. The standard for hardboard siding, ANSI A135.6 (11), defines the principal types of siding and the inspection and normal quality control test procedures related to the product. These tests are weatherability of both unprimed and primed surfaces, water resistance, linear expansion, nail-holding tests, bending strength, hardness, and impact resistance.

In addition to the previously noted safety factors associated with these processes, there are additional needs for dust control and ventilation for dissipation of various vapors from pressing, tempering/heat treatment, and machining and finishing operations.

6. Particleboard

6.1. Production, Processing, and Shipment

Particleboards are composites made from particles or small pieces of wood or other lignocellulosic residues, in contrast to the fibers used in the various types of hardboard, and the former are bonded together with an adhesive under heat and pressure. There has been a long debate over the origin of particleboards. At least 5 patents between 1880–1930 describe a form of particleboard, long before an economical adhesive was available.

When it was discovered that the polymer of urea–formaldehyde (UF) could be used as an adhesive, it quickly became the binder of choice. Particleboards were first made commercially in Europe in the late 1930s and the industry expanded significantly in Germany during World War II. The industrial technology came to the United States after 1945 and has grown steadily in both size and product quality. The primary benefit of the product is that it provides a necessary and useful outlet for the majority of the previously unused wood residues such as sawdust and planer shavings, as well as some chips from sawlogs and veneer logs. Small amounts of urban wood waste and low value logs are also used.

Particleboards are made in thicknesses of 3.2–44.4 mm (1/8–1 3/4 in.), with the bulk of production going into the 12.7–19.1-mm (1/2–3/4-in.) range. Particleboards are made across a wide range of densities, 415–1000 kg/m^3, with a generally inverse relationship between thickness and density prevailing. Figure 7 shows a general flow diagram of the particleboard process.

To begin the process, the particulate raw materials are rough-screened to remove oversize materials. The oversize materials may be used as fuel or processed through a grinder and returned to the screen. Also, there should be a unit in this area to remove rocks and trash metal. The material then moves to the milling/drying/screening area (material preparation area). It should be noted that from this point to the mat-formers, materials usually flow in two streams, one of smaller particles for the surfaces of the board and one of larger particles for the core or middle of the board. Milling generally precedes drying because a better mix of particle sizes is achieved if material is milled when still wet or moist. However, dry milling requires less power and some manufacturers prefer this sequence, even though more fines (small particles) are generated. If dry planer shavings are part of the mix, they will necessarily be milled dry. Another advantage of drying preceding milling is that it allows for separation of grit (dirt, sand, etc) following drying, which reduces wear on grinding equipment and also reduces the chance of fires occurring during milling. Grit removal is not easily done on wet or moist particles. Particulate milling is done by hammermills, impact mills, refiners with special plates, or knife-ring flakers. The knife-ring flaker is a machine designed to make flakes (long, thin, flat particles) from larger residues, such as chips. The other forms of mills use attrition or impact to break up the particles, and a much smaller mix of particles is generally obtained. In a few cases where small logs are used as raw material, these are first debarked and then flaked in large drum or disk flakers. The bark is usually used as fuel.

Drying is almost always done in large, rotating drum dryers. Heat can be provided from direct flame oil, gas, or wood dust burners, or from heat exchangers using these same sources of heat. A modern mill is typically designed to generate as much heat as possible from otherwise unusable wood and bark sources. The wood particles enter the dryers at the hottest (heat inlet) end and proceed through the dryers in a tumbling fashion, carried along by the flow of hot air. Temperatures will be about 540–760°C at the inlet and 200–430°C at the outlet. Dry moisture content of surface material will be at 4–6% mc and core materials at 2–4% mc. After the dryer, particles are separated from the moist, warm air in a series of cyclones. The dryer air then passes through a pollution-control system to remove dust and volatiles, so that the only significant emissions from the dryers are warm air and steam.

A measurement of particle moisture content will normally be taken at the exit of the dryer. This allows the process operators to make such adjustments as may be needed to maintain moisture within the desired range. Various instruments are used, none of which are entirely satisfactory, and periodic hand samples are used in some mills. Considering the importance of moisture sensing and control at the dryers, it is unfortunate that a truly efficient, consistent, and accurate sensing system is not yet available to the industry. The primary reasons for the difficulty of measuring moisture at the dryer exit are the extreme and adverse conditions of heat, dust, and moisture present at this location.

At this point, the dry particles and flakes may pass through a system designed to remove grit. To avoid excessive wear on saws and milling machinery downline and especially for the sake of safeguarding customers' equipment, it is necessary to have a grit (silica) level less than 0.05%, and preferably less than 0.03%. In these days, when more emphasis is being placed on recycling of urban waste woods, grit and metal removal equipment is a necessity for those mills reusing this resource. If the grit is primarily very fine material, it

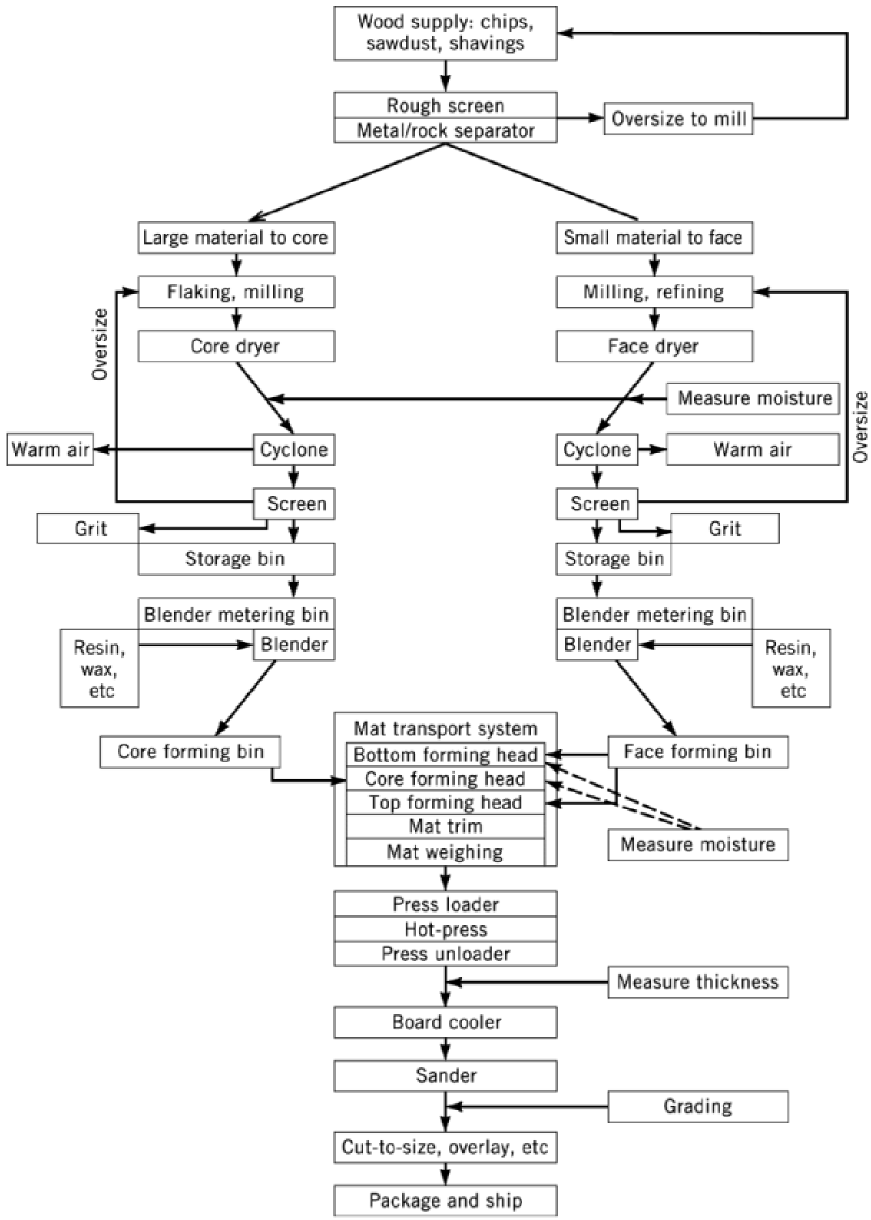


Fig. 7. The particleboard process.

can be removed by a small screen with only small wood losses, and these can be used for fuel. If larger grit is present, more sophisticated equipment is required.

The dry material then passes to the screening area where separations are made, based primarily on suitability as surface (fine fractions) or core (coarse fractions) materials. Oversize materials also is removed and returned to the milling area. After screening, the materials are stored in large bins or silos which provide several hours of running inventory so that the manufacturing process can continue if a breakdown of short duration occurs in the milling/drying area. The storage capacity should not be too large, as there is a danger that the raw materials will adsorb moisture and become too moist to allow the process to continue efficiently.

From the storage units, the raw materials are metered at desired and uniform flow rates to blending area. Blenders are normally large tubes employing a rapidly rotating central shaft with mixing paddles attached. Additives such as UF resin, wax, scavenger, and catalyst or buffer are metered into the blender and are mixed by the paddles as the material proceeds through the blender with the desired objective of uniformly mixing the proper amount of additives on all surfaces of the particles. Typical additives used in relative amounts as a percent of dry wood weight are given in Table 2.

Table 2. Additives Used in Production of Particleboard as a Percentage of Dry Wood Weight

Component	Face, wt %	Core, wt %
UF resin[a]	7–11	5–9
wax[b]	0.25–0.75	0.0–0.5
scavenger (urea)[c]	0.4–0.8	0.2–0.5
catalyst (ammonium sulfate)[d]	0.0–0.2	0.0–2.0
buffer (ammonium hydroxide)[e]	0.0–0.3	0.0–0.3

[a]Resin solids based on dry weight of wood.
[b]Wax solids based on dry weight of wood.
[c]Urea solids based on dry weight of wood.
[d]Catalyst based on liquid-to-liquid weight with resin.
[e]Buffer based on liquid-to-liquid weight with resin.

A small amount of water may also be added to improve blending or to assure proper furnish (blended materials) mc. Actual amounts of resin and wax used in a specific operation are based on amounts needed to produce the desired strength and water-resistance properties. Wax provides, in addition to water resistance, a small amount of lubricity, which aids in moving the materials through the process. The scavenger, normally urea, is added to react with excess formaldehyde from the resin and prevent excessive formaldehyde emissions from the product. In some cases, resin suppliers have been able to formulate resins with extremely low emission potential and thus avoid the additional step of adding an external scavenger. The amounts of catalyst (cure accelerator) and buffer (cure retardant) used must be balanced to meet the requirements of the system. Catalyst is used to hasten the cure of the core adhesive, along with the possible use of small amounts in the surface. Because catalyzed resins are sensitive to temperature, amounts are often changed on a summer-to-winter basis. Careful control is required to balance the need for faster press times and more production, with possible precure of the resin occurring before pressing. Resin durability problems may also be associated with too much catalyst remaining in the board after pressing. Resin suppliers also have proprietary catalysts and buffers which can be added during resin manufacture and in some cases can tailor a resin to the specific needs of the mill so that external catalysts and buffers are unnecessary. Moisture content from the blenders after wax and resin addition should be 9–11% for surfaces and 6–8% for core.

The blended materials, now called furnish, move from the blenders to the formers. A typical mill will have 3–4 formers, one for each surface (top and bottom layers) and one or two for core (middle layer). A mat-carrying plate or caul will pass under the former. This caul will be preweighed and the weight entered on the forming line computer. The caul may be a sheet of steel or aluminum, a wire screen, or a plastic sheet and will generally be the size of the hot-press. On some of the newer systems, the mat-forming and transport system may be a continuous wire screen. The speed of the caul system is such that enough mats may be formed in the time required to press a load of boards, the objective being to maintain the formers in a constant and uniform state of operation. As the caul enters the first former, a layer of fine surface particles is spread uniformly on the caul. The layer will be 20–25% of the panel weight and, depending on the type of former used, may be distributed in such a way that there is a gradation of finer particles on the bottom surface, ranging to coarser particles at the top of this layer. A desirable characteristic of particleboards is a smooth surface, and finer particles on each surface help to achieve this goal. A moisture sensor is often located between the first and second formers.

The caul now moves under the core former(s), where a layer of coarser particles is distributed. This layer represents 50–60% of the board weight. A moisture sensor is often located after the core former(s). A weight sensor may be under the line to sense the additional weight on the caul at this point. Finally, the caul moves under the top surface former and a final layer of fines is distributed atop the core layer. This layer will also be 20–25% of the total mat weight, generally equivalent to the amount formed as the bottom surface. As the caul moves out from the last core former, there is another weight sensor. Given the initial caul weight plus the two weights during forming, the system can easily be adjusted to maintain uniform mat weights by ensuring that the proper amounts are applied by the face and core systems.

After the mat is formed, it may move through a mat precompressor, if this is a feature of the line. Then the mat is trimmed to width and length. If the line does not have the in-line weight sensors noted previously, the trimmed mat will be weighed in total at this point. Mats which are off-weight for the target density and thickness will be dumped and the furnish recycled through the system. Normally, when the line is in uniform operation, very few mats will be off-weight. Mats then proceed to the press loader and into the press. Blended furnish should optimally be formed into mats and be ready to press within 15–20 min after blending. Unless special precautions are taken and special resin formulations, including buffers, are used, material which does not reach the press within 30 min should be dumped and then recycled through the process. It should be apparent how even a short (10–15-min) interruption in operation (downtime) can easily extend to 45–60 min or longer, owing to complications incidental to the interruption.

The pressing operation in a composites facility is a critical one from many standpoints. The amount of high quality board made determines the productivity and profitability of the operation. Thus, it is important to use a press cycle which is as short as possible while producing high quality board and maintaining a consistently uniform operation. But a short press cycle does not ensure high productivity if a number of short interruptions in production occur on each shift. The operators must learn what the optimum speed of operation is in their facility, with the objective of using the press as the slowest point or “bottleneck” in the process. In this way, the press is the only unit in the system which is operating at maximum speed, and thus allows the other equipment to operate at lower and generally more uniform and efficient rates.

Hot presses vary widely in size and number of openings (panels pressed during one cycle). A small size would be 10 openings of 1220×2440 mm $(4 \times 8$ ft.). The largest size is 24 openings of 2440×7315 mm $(8 \times 24$ ft.). A few single-opening presses may still be found. A recent development is the continuous press, which has two opposing heated steel belts which transport, press, and cure the adhesives as the mat is moved through the press. This is an expensive but highly efficient method of pressing.

The press may operate over a wide range of temperatures, 132–190°C a range of 154–177°C being most common. Higher temperatures allow faster production, but can create other problems if the facility is not specifically designed for these temperatures. Low temperatures are generally only used for thin, high density products which will blister (develop small bubbles) at higher temperatures. A typical press cycle for a 19 mm (3/4 in.) board is as follows, beginning with the press in the open position:

Step	Operation	Time, s
1.	unloading and loading the press	15–30
2.	closing the press to mat contact with platens	5–15
3.	closing the press to final board thickness	30–60
4.	maintaining thickness as adhesive cures	180–210
5.	decompression	10–20
6.	opening the press	10–20

Typically, steps 3–5 require 10–12 s/mm of thickness (16–19 s/1/16 in.). It should be apparent that reducing time in steps 1,2, and 6 to minimums is well worth the effort. The combined time in these steps is known as dead time, and mills which have dead times of 60–70 s are at a distinct disadvantage compared to those with dead times of 30–40 s. Another type of press worthy of mention is the steam-through or steam press. In the case of this press, thus far limited to single-opening presses, live steam is forced into the mat through a pattern of numerous small holes in the platen surface as the press is closing. The steam heat almost instantly raises the temperature in the entire board cross-section to a point at which the adhesive cures and thus decreases pressing times dramatically. The process works equally well with particles or fiber, but not as well as with large flakes or strands. One possible disadvantage is that density gradients through the thickness are very uniform and thus the products are not well suited to applications requiring high surface densities. However, for thick, low density products such as door cores, the steam press process has no competitors in terms of overall efficiency.

Desired mat moisture contents of 9–11% for faces and 6–8% for cores are generally accepted. UF resins cure best in a moisture regime of 8–9% mc. An 11% mc surface and 6% mc core are an excellent combination because the high moisture in the surface heats quickly, allowing the surface to compress optimally as well as converting the moisture to steam, which penetrates and heats the core quickly. Too little moisture, as in the case of a dry surface, slows the rate of heat penetration and extends the press cycle. Too much moisture (a more common condition) often requires a significant extension of pressing steps 4 and especially 5 to allow moisture to escape before opening the press. If this is not done, the boards will delaminate (blow) when the press is opened, which may result in the loss of the entire pressload. A severe blow may also cause downtime as the damaged boards are removed from the system. Thus it should be emphasized that success in moisture control is the most important factor in determining the ultimate efficiency and profitability of the operation.

As the panels leave the press area, they may pass through two sensing units. The first is a blow detector, which can locate delaminations that may or may not be seen by visual inspection. Boards with blow areas are marked for removal and then are usually ground up, remilled, and recycled through the process. The second unit is an automatic thickness sensor which, by means of several sensing heads across the board, measures and averages the thickness across and along the board. These thickness measurements and the mat weights taken before the press inform the operators if the product is in the proper thickness and density range and whether or not adjustments need to be made. This is the first product quality monitoring step and it is critical in achieving maximum production of on-grade panel materials.

Panels then move into a cooling device, normally a wheel or rack, where they are held individually and air is circulated between them to remove the majority of heat remaining in the boards after pressing. It is desirable to reduce the average board surface temperature to about 55°C. This temperature is sufficient to complete the cure of adhesive in the core of the board. The heat also helps to redistribute moisture uniformly within the boards, because the board surfaces are drier than the core when the boards come out of the press. Warm boards are normally stacked for several hours to a day to allow for resin cure and moisture equalization.

From these stacks the boards are sanded to final thickness. Most modern sanders can sand to a panel average target thickness ± 0.2 mm ($\pm$ 0.008 in.). Sanders are multihead machines, with sanding grits proceeding from coarse to medium to fine. The total thickness removal (sandoff) needed to reach a uniform, smooth sanded surface can be from only 0.75 mm (0.030 in.) on boards from a continuous press to more than 2.5 mm (0.100 in.) on an older multiopening press. Average sandoff on panels from multiopening presses is 1.8–2.1 mm (0.070–0.085 in.). The sanderdust may be recycled into the product, but is more commonly used for dryer fuel. After sanding, boards are visually inspected to remove panels with visible defects such as resin spots, visible blows, or other noticeable marks which affect surface quality.

Boards then proceed to the final processing steps, including trimming to the exact desired sizes, stacking, strapping, and shipping. Some orders may be for cut-to-size of smaller panels, and some mills may also have facilities for filling the surfaces to provide exceptionally smooth, ready-to-finish surfaces.

6.2. Secondary Treatments and Uses

Particleboards are the jack-of-all-trades products for interior use panels. They have been and are being used for virtually every conceivable interior use for which panels or strips of material can be used. The principal desirable features of particleboards are flat, smooth, warp-free, stable, and cost-efficient panels. They have good strength, stability, and screw and fastener holding abilities. They are almost ideal substrates for most finishing or overlay systems. They are available in many thicknesses and panel sizes and can be easily worked with good wood-cutting, molding, shaping, drilling, and vee-grooving equipment. To put their versatility into the perspective that is their due, it would be safe to say that the vast majority of homes and businesses in the United States contain a number of products in which the basic substrate is particleboard.

The majority of particleboard is used in furniture and cabinetry. A significant amount is used as floor decking in manufactured homes and as underlayment in conventional homes. Particleboard is used as shelving in homes and industrial businesses, as door cores in solid core doors, in stair stepping, door frames, and a host of uses requiring small flat parts as a starting point.

A small amount of particleboard is made with a fire-retardant treatment for use in locations where codes require this material, as in some offices and elevators. Particleboards receive overlay and finishing treatments with ease. Wood veneers, melamine overlays, printed paper overlays, vinyl overlays, foils, and direct grain printing can all be done quite simply. A small amount of particleboard is also made in the form of shaped, molded articles such as furniture parts, paper roll plugs, brush bases, and even toilet seats. There is another small increment of particleboard made by the extrusion process. These products are made in small captive operations owned by furniture manufacturers which consume all of this production in their furniture. The extrusion process differs from conventional flat-pressed particleboard in that the wood furnish is forced between two stationary heated surfaces. The mats are formed from one edge and this edge is alternately formed and pushed between the heated platens, which are maintained at a distance equal to the thickness of board produced. This is an old, slow, small-scale process, but is still in use in at least one location.

6.3. Economic Aspects

In 1994 there were 45 producers of conventional particleboard in the United States. These mills produced 8.205×10^6 m^3 of product (2). The real growth of the industry occurred in the period from the 1950s through the 1970s. The industry continues to grow slowly, with one new mill on the average being added annually. The major growth worldwide in traditional particleboard markets is occurring in the medium-density fiberboard area.

6.4. Specifications, Standards, Quality Control, and Health and Safety Issues

The particleboard industry is represented by the National Particleboard Association. Specifications, standards, and quality control (QC) procedures are outlined in *Particleboard*, ANSI A208.1-1993 (14). There are five grades of particleboard, with 1–4 subgrades within each group differentiated by physical property differences. These are requirements for bending and stiffness strength, bond strength perpendicular to the surface, hardness, screwholding properties, linear expansion, and formaldehyde emission. All of these properties are included in a normal QC regimen of tests. Physical properties test procedures are outlined in ASTM D1037-93 (15). Formaldehyde test procedures are found in ASTM E1333-90 (4).

In addition to the always-present concerns for worker safety around hot or moving machinery, additional measures are warranted by the dusty conditions that generally prevail around a particleboard mill. Great care is exercised to address the conditions through the use of cyclones and baghouses to trap dust and prevent its release into and around the mill environment. However, constant clean-up is necessary to prevent excessive dust buildup, which left unchecked can become a fire and explosion hazard. Most equipment which could start a fire or cause an explosion if foreign material were to create a spark within the system is protected by spark-detection and automatic fire suppression equipment. Conveyors are equipped with pressure-release hatches to reduce the danger of fire and explosion traveling throughout the system. Some workers in dusty areas wear dust masks. Most workers wear safety glasses and often make use of hearing protection devices, safety shoes, and hardhats. Advances in UF resin technology and use of scavengers have made concerns about formaldehyde exposure almost nonexistent in both mill and product use environments.

7. Medium-Density Fiberboards

7.1. Production, Processing, and Shipment

Medium-density fiberboards (MDF) are panels made of fibrous raw material and used in most of the same applications as particleboard. MDF products generally have more smooth surfaces and edges than particleboards and are thus preferred for some uses, even though the manufacture of MDF is more costly and the product is significantly more expensive.

Historically, MDF was developed in the United States in the 1950s. After a slow start, the industry grew most rapidly in the 1970–1990 period and has grown slowly in the United States since then, giving indications of significant potential for expansion in the 1998–2000 period. In recent years, other countries throughout the world have also recognized the favorable traits of MDF and many more plants have been and are now being built, particularly in Europe, Asia, and the South Pacific areas.

The manufacture of MDF, with a few exceptions, duplicates the manufacture methods for dry-process hardboard, described at length herein. One exception to it is that most MDF is made in the medium-density range, 640–800 kg/m^3 although small amounts are made at lower or higher densities. Second, the vast majority of MDF is made with UF resin adhesives with resin requirements in the 7–11% range, and wax is usually added at the 0.50–0.75% level. A small amount of exterior-grade MDF is made with isocyanate resin.

The major difference from dry-process hardboard manufacture is in the pressing area. Because MDF is usually a lower density product, lower pressing pressures are needed, and presses are not quite so robust compared to the dry-process hardboard presses. Also, some early MDF presses used primary steam heating and secondary heating systems based on radio-frequency (RF) heating. The use of RF heating allowed the center of the board to heat almost as quickly as the surface, and this occurred during closure of the press. Thus, the heated core, would compress almost as easily as the faces, which resulted in a quite uniform density profile through the thickness of the board. This then produced the appearance of a uniform, smooth edge when cut or machined.

The other major benefit of RF heating was in reduced presstimes. A typical steam-heated MDF press was operated at about 163°C. Presstimes, not including deadtime, for 19-mm (3/4 in.) board would be about 7 min. With RF, this time could be reduced to about 5 min. It will be noted that these presstimes, even with the use of RF, are longer than those required for particleboards and this, in addition to the more costly base fiber and the higher resin requirements, explains much of the manufacturing cost differential between MDF and particleboard.

After pressing, the MDF process basically duplicates the particleboard process with the steps of cooling, sanding, trimming, cut-to-size, stacking, strapping, and shipping.

7.2. Secondary Treatments and Uses

MDF competes with particleboard in virtually every application, especially in furniture and cabinetry. However, MDF is not used as floor underlayment or decking except on special request. The popularity of MDF is the result of the smooth surfaces and smooth-cut or machined edges. For applications such as direct grain printing, laminating with thin overlay papers or foils, application of smooth, gloss finishes, or uses requiring smooth, highly machined edges, MDF is the product of choice.

The exterior form of MDF is used in special applications requiring durability and resistance to water or weather exposure. Highway signs would be an example of this use of exterior MDF. It is an extremely expensive product and thus is used only for special applications requiring its special properties. Another example of use would be where a customer would be willing to pay the additional cost to use a composite which has the exceptional qualities of MDF, but also has virtually no formaldehyde emissions.

7.3. Economic Aspects

In 1994, there were 14 producing MDF mills in the United States. These mills produced 2.240 million m^3 of product (2). The market for MDF in the United States is fairly well saturated at this time and for this reason the industry is expanding only slowly. However, as noted herein, the world market is still growing rapidly and the manufacturers are building to satisfy this market. Currently, some U.S. manufacturers are also exporting MDF into these markets.

7.4. Specifications, Standards, Quality Control, and Health and Safety Aspects

The MDF industry is represented in the areas of specifications and standards by the NPA. Specifications and standards are found in *Medium-Density Fiberboard (MDF)*, ANSI A208.2-1994 (13). There are four classes of MDF, three classes divided by density and one for exterior-bonded MDF. Primary properties outlined in the standard and used in QC tests are bending strength and stiffness, bond strength perpendicular to the surface, screwholding properties, and formaldehyde emissions. Strength tests are described in ASTM D1037-93 (12) and formaldehyde emissions in ASTM E1333-90 (4).

The health and safety issues outlined herein for particleboard also apply to MDF. A special note should be made of the fact that, because the MDF raw material is of dry fiber base, there exists in MDF a large component of very small, broken, dust-like wood fibers. These contribute to the dust concerns in the manufacturing areas, requiring excellent dust-control systems, good housekeeping, and personal protection.

8. Waferboards and Oriented Strand Boards

8.1. Production, Processing, and Shipment

The waferboard and oriented strand board (OSB) industries are based on the use of special forms of wood flakes generated from small logs. A flake is a long, flat section of wood which may be 25–100 mm (1–4 in.) in length and in the grain (longitudinal) directions of the wood. Thickness may be 0.25–1.00 mm (0.010–0.040 in.), and width is usually variable. Normally, a good flake has a length-to-thickness ratio of at least 100.

Wafers as used in the industry were large, flat flakes of about 0.6–1.0 mm (0.025–0.040 in.) in thickness, 38–50 mm (1 1/2–2 in.) in length, and 13–50 mm (1/2–2 in.) in width. Strands are long, narrow flakes of about 0.6–1.0 mm (0.025–0.040 in.) in thickness, 75–100 mm (3–4 in.) in length, and 6–25 mm (1/4–1 in.) in width. Variation will occur around these dimensions, but these will apply in the case of the majority of the waferboard and OSB products.

Flakes and flakeboards have long been a source of attention and interest to the industry, because excellent strength and stability can be achieved with boards made from flakes. However, the requirement of solid wood as a starting material and uneven swelling properties of the boards prevented them from becoming an economical or desirable product for use in many particleboard applications. Nevertheless, at least seven 1950s era particleboard plants operated on large flakes as part or all of their raw material. Decorative paneling was probably the most successful product of this production, but eventually all went out of production because they could not compete in the standard particleboard markets. In 1955, a plant was built in Canada utilizing the technology of an earlier U.S. mill: large flakes or wafers bonded with powdered PF resin adhesive. The market was low cost, exterior sheathing panels called Waferboard for barns, sheds, fences, etc. Time spent in exposure proved that the panels were entirely satisfactory for these uses; in fact, many of these structures are still in use today. Over the succeeding years, a few more plants were built, mostly in Canada.

Then, in the early 1980s the concept of OSB was realized in the construction and operation of large-size mills. OSB is a panel product made from wood strands and somewhat like plywood in that the strands on the two faces are oriented in the long direction of the panel and the core strands are oriented in the cross-panel direction. The use of orientation yields panels having excellent directional properties, much like plywood, and thus an excellent and economical structural sheathing material is created.

The manufacture of waferboard and OSB has many of the same process steps as particleboard, but adapted to the special needs of producing an exterior quality panel with large wafers or strands. This discussion focuses on OSB, because waferboard has been almost entirely replaced by OSB and most of the early waferboard mills have now been converted to production of OSB. The OSB process is outlined in Figure 8.

The process beings with small logs of almost any species. Aspen was the preferred species for years but now the industry has spread well beyond the range of aspen growth and any species which can be converted to strands has been used. High density hardwoods such as oak, hickory, and hard maple are avoided where possible, because of the difficulties in flaking. The logs to be processed are debarked and the bark used for fuel. The debarked logs are placed in soaking tanks which will be heated in winter to thaw and heat the frozen logs. As the logs reach the end of the soaking tanks, they are removed and prepared for the flakers. Flakers are of two types, the first using huge rotating disks containing a number of long knives extending outward from the axis of the disk. These knives protrude from the face of the disk by the desired flake thickness. There are also small, sharp spur knives protruding from the disk at intervals equal to the desired flake length. Log sections are fed into the disk and each knife removes a slice from the log. The spur knives cut the slice into many separate lengths, and these pass through an opening in the disk. As the slices pass through the disk, they encounter special metal shapes which bend, buckle, and break the slices into narrow strands which fall into a conveyor below and behind the disk. Another type of flaker is a revolving ring flaker. The ring is about 600 mm (24 in.) in depth, with many flaker knives and spur knives protruding inward on the inner periphery of the ring. Logs or log sections are pressed against the inner periphery as the ring rotates. Slices of wood are removed and are again broken into strands as they pass through the ring and fall into a transport conveyor. Recent developments have made it possible to flake whole logs one section at a time in both of these flaker types.

The strands move through large drum dryers which reduce the moisture content to about 2 or 6%, the difference being whether liquid or dry resin is to be used. Because a desired moisture level into the press is about 6–7% mc, a liquid resin adds water to the system and requires a lower flake moisture than a dry resin.

From the dryer, the strands are screened to remove fines and small particles, which would detract from board quality and economy. These fines are burned for fuel or possibly sold to a nearby particleboard mill as raw material. The larger strands are used as surface material and the smaller strands are core material.

The strands are metered from the bins into the blenders, which are large rotating drums which tumble the flakes as they move from the infeed to the exit end. Resin adhesive and wax are applied; if dry, powdered PF is applied, this is accomplished by a simple metering system which meters the powder at a rate proportional to strand flow rate and at a level of 2–2.5% by weight of dry wood. Other liquid additives are normally applied by centrifugal disk atomizers rotating at high speed and generating a mist of additives which attach to the surfaces of the tumbling strands. Wax is applied at a 1–1.5% rate to provide water repellancy in the finished product. Liquid PF adhesives are applied to rates of about 3.5–4.0%. Another binder being used in some locations is isocyanate resin. It may be used in the entire board or it may only be used in the core of the board with PF-bonded surfaces. Usage rates are 1.5–2.0%. Isocyanates have several desirable features, such as excellent bonding abilities, high moisture tolerance, faster curing than PF, and lower adhesive usage than

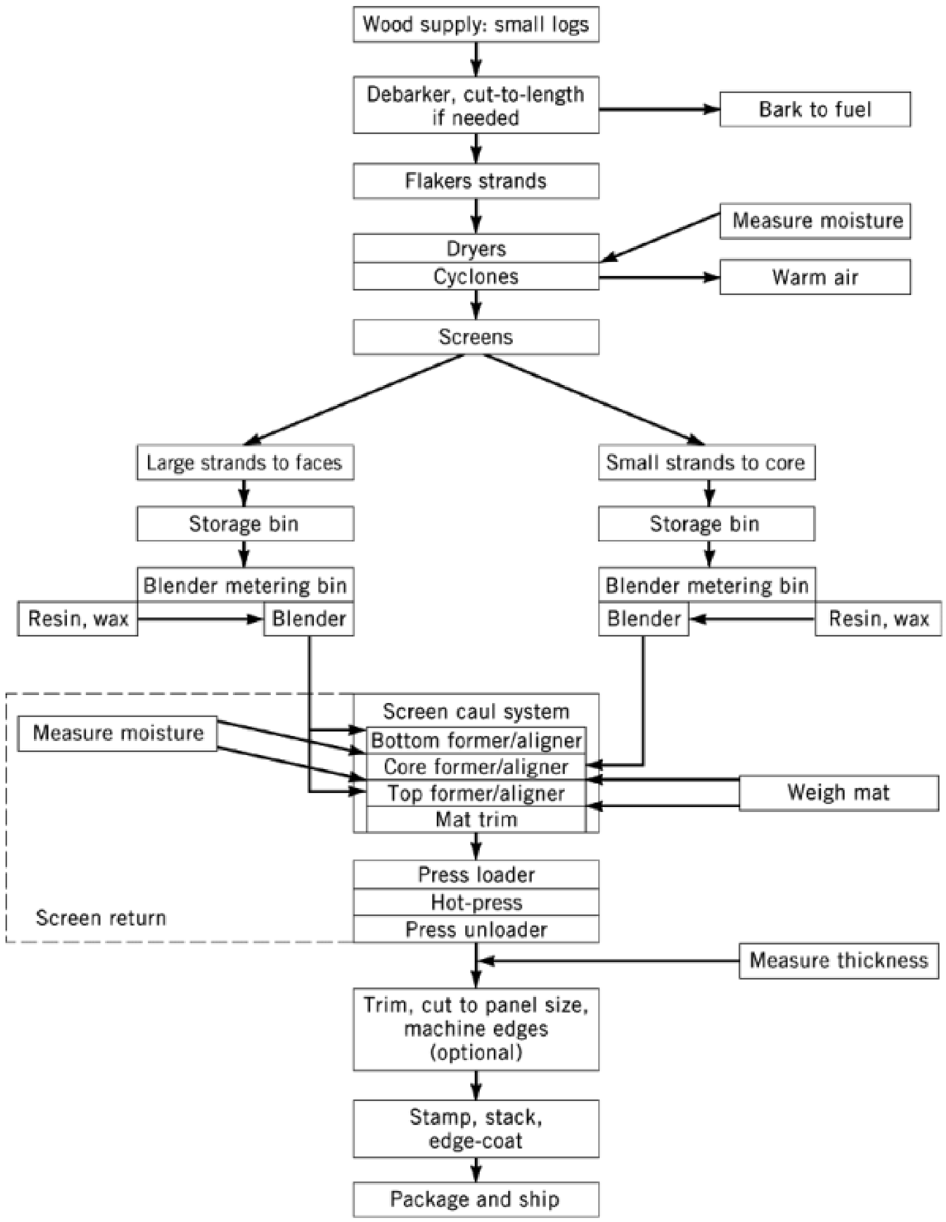


Fig. 8. The oriented strand board process.

PF. Less desirable attributes are press sticking potential, high cost, and workplace health and safety concerns. Press sticking can be avoided by use of isocyanates in the core only where faster cure rate also helps to offset the added cost.

Strands move from the blenders to the formers. Mats are formed on wirescreen cauls. The major benefits of screen cauls are long working life and as an aid to removal of moisture in steam formed during and immediately after the press cycle. This dramatically reduces the tendency of these large strand products to blow after pressing. An unintentional benefit was the embossed screen imprint in the board, which when placed screen-side-up on roof sheathing installations, provides a slip-resistant walking surface for workers. As the screen-cauls pass under the formers, the lower surface strands are placed on the screen-caul such that they are generally aligned with the long direction of the screen. This is done by dropping the strands between rows of closely spaced, rotating metal disks located just above the screen caul. The core strands are then laid down so that their lengthwise dimension is generally perpendicular to the surface strands. Finally, the top layer of strands is applied to the mat, also in the long direction of the screen and mat.

Mats then move to the press loader and into the press. Presses in OSB plants are usually very large, with panels of 2440×7320 mm (8×24 ft) a common size. Newer plants produce panels of 3660×7320 mm (12×24 ft). Presses will produce 8–16 panels of these sizes in one pressload. Press temperature are 204–218°C for pressing PF-bonded panels, but temperatures as low as 190°C can be used when isocyanate adhesives are used. Press times, not including deadtimes, with PF-bonded panels are about 14–15 s/mm of thickness. With isocyanate adhesives, presstimes are reduced to about 12 s/mm of thickness. The presses are equipped with elaborate position-control systems so that all panels will be close to desired thickness as they exit the press. Panel densities will range from 575–675 kg/m^3, depending on wood species used and end-product use requirements. The objectives are to reduce panels to minimum densities consistent with good quality and end-use requirements. This extends the resource, as well as easing handling in the field.

After the press, the panels are immediately cut into ordered sizes, the most common of which is 1200×2440 mm (4×8 ft.). Panels are then printed with appropriate use information, stacked, and usually edged coated with a moisture-proof barrier coating prior to banding and shipping. The edge coating provides protection from moisture damage on panel edges during shipping and field installation of the panels.

8.2. Secondary Treatment and Uses

The vast majority of OSB panels are used “as is,” without further processing or treatment. Primary uses are as wall and roof sheathing, floor decking, and other construction panel uses in home and commercial construction. OSB products are effectively filling in for the decline in plywood production. Small amounts of OSB are used in furniture, primarily as frame stock, and in other uses in which plywood might be used.

The major secondary use of OSB has been the production and marketing of an OSB exterior wall-paneling or siding. This was done by applying a PF-resin impregnated paper on the top of the strand mat immediately before pressing. The paper overlay was then bonded to the mat during pressing and embossed with a rough-sawn wood grain pattern in a manner similar to that used for hardboard siding. Panels were then sawn into strips, coated with a paint primer, and sold as lap siding. Another competitive product was made with a layer of adhesive-coated fiber bonded to the top of the strand mat in the press. This product was also embossed in the press and then primed and sold as lap siding strips.

8.3. Economic Aspects

There were 31 OSB plants in the United States in 1994 and these produced 6.625×10^6 m^3 of OSB products (2). This industry is growing rapidly in both Canada and the United States. In fact, many of the composite mills currently under construction are designed to produce OSB or similar products based on strands. Outside of North America, where building practices are not yet extensively utilizing the distinct advantages of the stud wall and plywood/OSB sheathing, there are only a few operating OSB plants. There are also small export markets for OSB products in Europe and the Far East.

8.4. Specifications, Standards, Quality Control and Health and Safety Aspects

The OSB industry is represented by the APA—The Engineered Wood Association in areas of specifications and standards. These are outlined in APA *Performance Standard for Wood-Based Structural-Use Panels*, PS2-92 (15). The standard defines specifications, qualifications, and tests for panels of any type which are to be used in structural-use applications. Thus, structural plywood, OSB, and all other similar products are considered to be covered by this standard. The major areas discussed in the standard are product classification, general requirements, and product evaluation and qualification. Twenty test methods are outlined and can be placed in the following general groups: bending and load testing, fastener holding, moisture and dimensional stability, mold and bacteria tests, probe tests, and cyclic durability tests.

Health and safety factors in the OSB industry are similar to those in other composite mills. Worker safety cannot be stressed too highly, a main component of which is to develop an awareness in the workers to be prepared for danger at all times. Many accidents are the result of a moment of careless or unthinking activity on the part of the person injured or another nearby person. An area of special concern in some OSB mils, those using isocyanate adhesives, is awareness of the toxic nature of this adhesive in the uncured state and the requirements of personal care, housekeeping, and ventilation and air handling in the process areas from blending through pressing.

9. Structural Composite Lumber

9.1. Production, Processing, and Shipment

Structural composite lumber is a group of composite or veneer products which can be used in place of structural lumber in many applications. These products and markets have been developed to fit specific needs of the construction industry where solid lumber of desired grades is no longer available or at least, very difficult to obtain. An important factor in the acceptance of these solid lumber substitutes is their uniformity. While composites in general may not be as strong as clear, straight-grain solid wood, they may be significantly stronger than knotty or angled-grain lower grades. Also, the variation in properties is much less than in run-of-the-mill solid lumber. Thus, in the design of wood structures for which a composite with known and predictable properties can be selected, as compared to a batch of lumber, in which the worst piece defines the batch, there is no question which material should be selected.

There are three distinct types of structural composite lumber available. The manufacture of each is discussed herein with emphasis on interrelationships between the products.

9.1.1. Laminated Veneer Lumber

Research and development on laminated veneer products resulted in manufacture of a marketable lumber substitute in the late 1960s. The product was made of many layers of 2.5–3.2 mm (1/10–1/8 in.) veneer bonded with PRF adhesive in a long continuous press. Panels 1220 mm (4 ft.) wide and 38–50 mm (1.5–2.0 in.) thick of endless lengths were made. Ends of the 2440 mm (8 ft.) long veneers were staggered through the thickness with a short overlap at the ends of veneer to provide a lap joint to transfer loads. Since that time, other manufacturers have entered the laminated veneer business. Some thicker veneers with various endjoints including butt joints and fingerjoints have been seen. Properly made, these materials approach the load carrying abilities of high grade solid lumber. Because of their reduced variability in strength, these laminated veneer products compare very favorably with the highest quality lumber.

9.1.2. Veneer-Composite I-Beams

One of the earliest applications of laminated veneer lumber was as flange stock in a veneer-base I-beam. Narrow strips, 50–100 mm (2–4 in.) were cut from the 1220 mm (4 ft.) wide panel and a groove about 9.5 mm (3/8 in.) wide and deep was cut in the surface of two of these strips, and the two strips were placed in a machine with a set distance separation between them. As the strips moved through the machine, a PRF adhesive was metered into the grooves. Then cross-cut sections of 9.5 mm (3/8 in.) plywood were placed in the grooves end-to-end to make web-stock for the I-beam. The strips were pressed together to seat the plywood in the bottoms of the grooves, and the assembly came out of the machine as a completed I-beam. As an example, a nominal 2×12 in. lumber replacement, actually 38×286 mm (1.5×11.25 in.), might have flanges 63 mm (2.5 in.) wide $\times 38$ mm (1.5 in.) thick and with a web of 229 mm (9 in.) to duplicate the 286 mm (11.25 in.) dimension of the solid lumber. In this way, beams of almost any grade and size can be made by changing the width of the flange and with width of the web material. In recent years, OSB has replaced much of the plywood as web material in these I-beams.

9.1.3. Laminated Strand Products

The most recent developments in the family of wood-based composites are a group of laminated strand products, made with strands oriented in the long direction of the product and marketed as structural composite lumber. One product is made with long, narrow strips of softwood veneer. The strips or strands are about $2.5 \times 13 \times 600$ mm ($0.1 \times 0.5 \times 24$ in.), coated with a PRF adhesive, and pressed under heat and pressure into large blocks. After the resin is cured the blocks are resawn and planed into lumber dimension stock.

Another product is made with strands produced by flakers, having dimensions of about $0.8 \times 13 \times 300$ mm ($0.030 \times 0.5 \times 12$ in.). The strands are dried and then coated with isocyanate adhesives. The strands are formed into mats with unidirectional orientation and pressed in a steam-through press. The large panels are then sawn into dimension lumber sizes.

9.2. Secondary Treatments and Uses

The structural composites lumber group requires little secondary processing to be used in the various construction areas for which they are intended. The products are being used in most of the applications formerly and almost solely filled by large structural timbers and large-dimension lumber. Some of these uses are as floor joists and roof trusses, both of which are ideal applications for the composite I-beam; building foundation timbers; garage door headers, as well as headers for large doors and windows; scaffolding planks and similar uses.

9.3. Economic Aspects

In 1994, there were 10 manufacturers of various types of structural composite lumber with a production volume of about 0.820×10^6 m^3 (2). Several more plants are now in production or under construction. Given the reduced availability of solid lumber in large structural sizes, this is another area of composite products having a promising future.

9.4. Specifications, Standards, Quality Control, and Health and Safety Aspects

In general, structural composites lumber products are tested and rated in the same manner as structural lumber. Strength in bending stiffness is possibly the most important characteristic, because this property defines the basic load-carrying capacity of the product. Tensile strength is also important, because this defines load-carrying under a tension stress, such as in the bottom chord or flange of an I-beam. Terminology, procedures for determining allowable design stresses, and quality assurance requirements are set forth in the ASTM *Standard Specification for Evaluation of Structural Lumber Composite Products* (D5456-93) (16).

Health and safety concerns in the structural composite lumber industry are similar to those in the other composite industries. Special care is required in worker awareness, worker protection equipment, dust and vapor control, and general housekeeping.

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