FLUID-PRESSURE MOLDING
OF PLYWOOD
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UNITED STATES DEPARTMENT OF AGRICULTURE
FOREST SERVICE
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In Cooperation with the University of Wisconsin
The molding of plywood by means of fluid pressure applied through flexible bags or blankets of some impermeable material (bag molding) has found application in making plywood parts of various degrees of curvature. In size, these parts may vary from a small aircraft fairing to a complete boat hull. Typical parts include all combinations of single and compound curvature, cylinders, paraboloids, portions of a sphere — in short, any curved piece for which a mold can be made and later separated from the finished product.

Bag-molded aircraft parts, such as fuselages, wing fillets, and fairings, are reported to offer improved performance characteristics as a result of the superiority of the stiffness-weight ratio of molded plywood to that of metal and the smooth ripple- and rivet-free surfaces presented to the air stream.

Bag molding of plywood and laminated veneer members probably had its origin in the vacuum-bag process that was introduced in the furniture industry several years ago (fig. 1, A). While the vacuum-bag process depended upon atmospheric pressure and ordinarily only room temperature to set the glue between the plies, the newer techniques employ higher fluid pressures and varying degrees of heat.

Misnomers, such as "plastic plywood" and "plastic planes," have been applied to structures of molded plywood that are actually made from wood veneers bonded with synthetic resin adhesive. By weight, these structures are probably about 80 percent wood and 20 percent resin adhesive. Except for variations in shape, the product is essentially the same as flat-press plywood.

Methods of Molding

Molded plywood is produced by several techniques which are often referred to specifically, as the Duramold, Vidal, Aeromold, or vacuum-bag processes. Other terms sometimes used in describing the technique are "bag-molding," "autoclave molding," or "tank molding." Perhaps the most inclusive is the term "fluid-pressure molding." Five general methods are shown in figure 1.
The fundamental procedure is the same for all processes in common use. In principle the technique consists of attaching temporarily by staples, tape, clips, or some other means, superimposed layers of strips or sheets of glue-coated veneers to a mold of the desired shape, and molding these into a unit structure by the application of heat and fluid pressure through a flexible, impermeable bag or blanket. All the processes are relatively simple and provide a means by which plywood of simple or compound curvature, and of constant or varying thickness, in any arrangement of plies can be produced.

Flat plywood can also be made by bag molding, but flat plywood can be produced more economically by other methods so that the bag-molding technique is largely limited in use to the production of molded parts that can be manufactured by no other practical means. In general, parts that fall in this category will have one or more of the following characteristics:

- Appreciable compound curvature;
- Variable thickness;
- Single curvature bends approximating or exceeding 180° (when pieces are too thick to be steam bent from flat plywood);
- Parts too large to be made practicably by mating dies;
- Quantity too small to justify mating dies.

The application of heat to the glue during the pressure period is the basic difference between present-day bag-molding methods and the older vacuum-bag process. The newer processes, therefore, permit the use of thermosetting and thermoplastic glues with long assembly periods. Most of these newer processes use pressures within the range of 30 to 100 pounds per square inch instead of only the atmospheric pressure used in earlier work. Figure 1 illustrates diagrammatically the processes in use at present: A, the vacuum-bag process, B, C, D, and E, techniques employing higher pressures and heat. There are numerous combinations of these five means of supplying heat and pressure. Most of the variations in methods in current use, as well as suggested possible techniques not yet in commercial use, are presented in Table 1, which gives the practical limitations of pressures and temperatures, and suggests bag and mold materials for each method.

The first three methods listed in Table 1 are used most widely and at present probably produce over 90 percent of the bag-molded plywood of aircraft or boat quality. All three methods require the use of bag materials that are steam-, water-, and air-tight under the conditions of temperature and pressure used. Perhaps 95 percent of the bag-molded plywood now being produced requires bags of natural or synthetic rubber. Cellophane bags have been used, but only experimentally, in these three methods.

Full utilization of rubber bag materials requires that bags be used to maximum life. Under these conditions, leaks developing from deterioration of the bag during the repeated application of heat and handling are unavoidable. Steam, steam-air mixtures, and water as heating and pressure mediums, when used with a leaky bag, cause considerable damage to the part being molded and often to the mold itself. This difficulty has prompted many users of the bag-molding technique to experiment with other fluids, such as air or inert gas, in their search for a more satisfactory pressure and heating medium. Gases have very low specific heats and using them to transfer heat to the part limits the rate of production. Furthermore, tests have
shown that hot air is particularly damaging to all rubber bags, consequently these heating mediums are most logically used in combination with cellophane or some other substitute bag material that is cheaper than rubber.

Bag leaks should be avoided regardless of the pressure fluid used. Preliminary tests have shown that even relatively small leaks can cause as much as 20 percent reduction in net pressure applied on the glue joints. The pressure loss depends upon the size of the leak and the restriction under the bleeder fitting.

When using a gaseous fluid as a pressure medium, the heating time can be greatly decreased if the mold is heated directly by steam or electricity. Heat is thus transferred to the glue lines by conduction rather than by convection. In this method, heat travels from the mold to the plywood and the bag stays relatively cool, thus broadening the selection of usable bag materials. Several methods listed in table 1 (6, 7, 10, and 11) offer these advantages and should be investigated carefully, particularly when it is desired to form a large number of parts successively on the same mold. In some cases (10 and 11, table 1) the mold is built to withstand internal pressure, therefore, no autoclave is required.

All the methods thus far discussed anticipate the use of pressures considerably in excess of atmospheric. It is possible under certain limited conditions to produce bag-molded plywood of durable quality using only a vacuum within the bag to develop the external pressure of the atmosphere. However, by this method, good results are obtained only with thin, flat veneers, on relatively flat molds, with a limited number of glues. Methods 12, 13, and 14 in table 1 might be used for this purpose. Low-temperature-setting glues with sufficiently low curing temperatures might also be used with the vacuum-bag process in a warm room in producing small parts that can be assembled in a relatively short time.

Equipment for Fluid-pressure Molding

Molds

The forming of any piece of fluid-pressure-molded plywood requires a mold of some type. Molds, sometimes called forms, dies, or mandrels, are broadly classified as male or female. Male molds as illustrated in figure 1, A, B, and C are the desired shape on convex surfaces, while female molds (fig. 1, D and E) have the proper shape on concave surfaces.

Common mold materials are wood (solid or plywood), metal (steel, cast iron, or low-temperature alloys), plastic materials, and cements. The choice of mold materials will depend largely on the shape of the item to be molded, the quantity desired, and the availability, advantages, and disadvantages of the materials considered.
Wood Molds

Wood molds are commonly made of softwood lumber, such as Western white pine or sugar pine, cut approximately to the contour of the mold and glued and nailed together. The rough shape, usually not more than 6 inches thick at any point, is then marked into stations -- a procedure very similar to that used in defining the shape of a boat -- and worked down by plane and sander to the desired shape minus an allowance for a hardwood skin. This hardwood skin (often of birch veneer) is bonded directly to the mold by bag molding and is later worked carefully down to the exact contour at each station. Attention is given to the direction of the grain in both the skin and the mold proper so that the maximum cross-banding effect is obtained.

Wood molds are distorted somewhat by repeated exposure to moisture and heat. A leaky bag results in damage to a wood mold and the piece being molded is usually ruined. Overheating the mold will hasten the distortion and necessitate early recontouring or other repair. Much of this distortion and cracking is caused by exposing the hot surface of the mold to the air after the removal of the molded piece from its surface. By cooling the mold while in the bag this rapid surface drying can be minimized. Cooling can be done by a cold water spray system in the cylinder or in a special cooling booth installed near the cylinder.

Plywood molded on thick wood molds heats more slowly than the same thickness and construction on thin steel molds. The time required to mold the piece, therefore, is about twice as long as for the same construction on a thin steel mold.

A variation of the wood mold construction that may be referred to as a "plywood-shell mold" is sometimes used. These molds are produced on a master mold of the usual lumber type. The shell mold itself is similar to the finished molded plywood article, only much thicker (3/4 to 1-1/2 inches) depending upon its size and the degree of curvature. The face veneers of these molds are sometimes impregnated with resin which is cured at the time of bonding.

Another construction that should produce a more stable mold involves the use of thick, resin-bonded plywood instead of solid wood stock in the body of the mold, with an impregnated skin of veneer bonded to the plywood base. The plywood should be laid so that its shrinking and swelling in thickness will introduce the least dimensional changes in the mold.

Wood molds are almost always male in shape, which necessitates fastening the strips of veneer to the mold to hold them in place on the convex surface. This is readily done by means of staples that must later be removed.

Wood molds are well adapted to the formation of a molded plywood aircraft or boat skin and permit bonding the skin to stiffeners or ribs in the molding operation. In this process the ribs are preformed by laminating or steaming to exact shape. They are inserted in previously cut slots in the face of the mold before the veneer strips are stapled in place.

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Metal Molds

Metal molds are usually made of sheet steel or cast iron. Alloys having low melting points are also reported to be in limited use. Molds of single or very slight double curvature are made of sheet material 1/10 to 1/4 inch thick, while those of severe double curvature, such as for an airplane tail cone, are often cast. Metal molds are very stable but those which are cast must be machined which makes them expensive and often difficult to obtain. In most cases, metal molds are of the female type in which the strips of veneer are taped together or sprung in place between metal clips, thus eliminating the necessity of a tacking surface to which material can be stapled.

Metal molds, particularly those of sheet metal, have the advantage of very rapid heat transfer. The rate of temperature rise in a molded plywood piece on a thin metal mold approaches that of plywood of the same thickness in a hot press. The time in the pressure cylinder, therefore, can be approximated from the hot-press instructions for the particular glue being used by adding the actual pressing time to the time required to bring the pressure cylinder up to operating temperature. Heavy cast metal molds heat more slowly than sheet metal molds but the heat transfer will probably be more rapid than for wood molds. For any kind of mold the rate of heating is affected by the heating medium.

Molds in continuous use may require cooling before they can be used for the next lay-up. This is particularly true of small metal molds of considerable thickness, and with this type, cooling is usually done with cold water. Large molded pieces require a longer time for removal, and consequently the mold may be sufficiently cooled before it is again ready for use.

Cement Molds

If a cement or concrete mold is used, a wood form must first be made to cast the section. After this is done it is sometimes necessary to bond to the mold a tacking surface of wood or possibly some other suitable material. Cement molds have the advantage of being stable towards moisture but are excessively heavy and cumbersome to handle and are damaged somewhat by repeated heating.

Plastic Molds

Some attempts have been made to use casting resins, and other materials which can be poured, in mold construction, but to date these uses have been mostly experimental and have proved practicable in relatively few cases.
The purpose of the bag or blanket is to provide a flexible impervious barrier between the fluid under pressure and the mold. The piece being molded is pressed between this flexible bag and the rigid surface of the mold and the full fluid pressure is applied at right angles to the surface of the bag regardless of the shape. The pressure at certain glue joints may be slightly less than the full fluid pressure by the amount necessary to shape the veneer or to force it into place.

Bags are classified as full bags or half bags (blankets). A full bag is a complete envelope of impervious flexible material (fig. 1, A and C) clamped shut at one end or side and having a connection, usually called a bleeder, to allow the entrapped air to escape to the atmosphere. It may be completely closed, similar in principle to a basketball bladder (fig. 1, B and D), having only a tube connection for inflation. A half bag, or blanket, is a sheet which normally fits the mold without wrinkling and is sealed by some temporary means to the edges of the mold (fig. 1, E). The bleeder may be attached to the mold or to the bag. Full bags are normally used over male molds and half bags are used on female molds.

Because half bags do not support the weight of the mold, abrasive wear is less and their life is greater than that of full bags. The use of fitted half bags is advised where production is high and they can be tightly sealed to the mold.

The useful life of a bag depends on the type of material used in the bag, the heating medium used, the temperature of the cycle, the size of the bag, and the care used in handling. It may be as short as 10 hours or as long as 200 hours of operation.

The type of bag and the material from which it is made depend largely on the molding process to be used, the temperature, and the heating medium. Most current bag-molding operations require bags made of specially compounded natural or synthetic rubber, often reinforced with fabric.1

Efforts are being made to find additional bag materials and means of increasing the production of molded plywood per pound of material used. In tests at the Forest Products Laboratory certain polyvinylidene chloride, vinyl butyral resin, and cellophane films have shown some promise as bag-molding materials. The use of short-lived materials necessitates the frequent attachment of bleeder fittings. Figure 2 illustrates a convenient metal bleeder fitting that has been used satisfactorily with rubber as well as other bag materials.

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1See partial list of bag material manufacturers in appendix.
Present information indicates that, in ordinary use on a steam-air cycle at temperatures of about 250° F., the life of a rubber bag is approximately 50 operations on a full, unfitted bag. Repair of minor leaks, usually caused by rough handling, may be necessary during this period. The use of hot water or pure steam for heating reduces oxidation and greatly increases the life of a bag. With a thick, fitted, half-bag assembly, considerably more than 100 operations may be expected in steam at 300° F.

Whenever a steam-air mixture is used and the air is introduced under pressure from a compressor, an adequate after-cooler and air filter should be installed between the compressor and the cylinder. When all traces of oil in the form of vapor or small drops are removed from the air, the bag life is considerably increased.

Tests at the Forest Products Laboratory have indicated that synthetic rubber bags are generally more resistant to heat, both dry and wet, than natural rubber. In these tests also, a steam-air mixture at 250° F. was found more damaging to all bag materials of rubber or synthetic rubber than pure steam at 300° F. or even 320° F. Where conditions permit a choice between these two heating mediums, the use of pure steam at 300° F. (52 pounds per square inch) is recommended to gain the advantage of a longer bag life and a shorter heating cycle.

Normal rubber bag thicknesses are between 1/32 and 1/8 inch, depending upon the amount of reinforcing, the severity of handling, and the type of bag molding. The thinnest bag capable of withstanding the handling and mechanical wear is recommended. A thin bag has several advantages; probably most important is its more rapid heat transfer. When thin bags are used, wrinkles in the bag are less likely to leave their marks on the bag side of the piece being molded. This is important with thin veneers, since a thick bag could easily produce an area of poor glue joint as much as 1/4 inch wide and several inches long as a result of reduced pressure under a fold in the bag. A practical guide, whenever bag wrinkles are likely to occur, is to use a bag no thicker than the face veneer. The economy of using thin bags is obvious, provided the bag is strong enough to withstand the handling.

In all bag-molding it is advisable to use a layer or two of paper, cloth, or canvas between the plywood being molded and the bag. This facilitates the "bleeding" of air and steam to the outside and also minimizes adherence of the glue squeeze-out to the bag. It is advisable to cover any sharp corners at the edges of the molded plywood piece with extra layers of canvas to prevent injury to the bag.

When a rubber bleeder hose is used, as in figure 1, C or E, it must not collapse and close when external pressure is exerted upon it during the molding cycle, if it is to fulfill its purpose. Collapse of the bleeder hose within the cylinder is difficult to observe. Emission of a slight amount of air or steam from the bleeder does not guarantee that it is functioning properly. A flexible metal hose, a copper tube, or a suitably reinforced rubber hose is recommended for the bleeder where this type of hose provides the necessary flexibility.

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In using the methods shown in figure 1, A and C, careful attention should be given the inside surface of the bleeder fitting in the bag. If this is very smooth and flat, it may make an airtight fit and stop the bleeder from functioning. Grooves in this fitting, as shown in figure 2, or a piece of coarse burlap glued to it, will usually suffice.

Pressure and Temperature Equipment

All pressure cylinders for use with bag-molding should be hydraulically tested to a pressure of at least double the maximum working pressure used. An adequate safety valve should always be installed if the pressure of the steam or air supply is in excess of the pressure at which the cylinder was tested.

The sensitive elements placed within the pressure cylinder for controlling and recording conditions should be carefully installed. Heavily jacketed controls will lag and therefore will not record the actual cylinder temperature during the rapid heating-up period. A jacketed thermometer was found in experiments at the Forest Products Laboratory to be as much as 30° to 30° F. below the reading on a bare thermocouple in heating a cylinder 2 feet in diameter and 6 feet long to 250° F. in 5 minutes, using a steam-air mixture.

If temperature stratification exists in the cylinder, a temperature-recording bulb at the top of the cylinder may be 30° F. or more above the actual temperature at the bottom of the cylinder; provision for circulation should therefore always be made if possible. A good check on uniformity of temperature may be obtained by inserting bare thermocouples in the top and bottom of the cylinder.

A large inlet for the heating medium is advisable, so that the cylinder can be brought up to the desired temperature and pressure in 5 minutes or less. This rapid heating is usually advisable and requires high boiler and compressor capacity for large cylinders.

Glues for Bag Molding

In selecting a glue for bag-molding operations close cooperation is urged between the user and the glue supplier to insure best results. The selection of glues for bag molding is often limited by the performance requirements of the product. Aircraft specifications on molded plywood and specifications for glue joint performance of marine plywood require glues of high durability.

Parts to which bag molding is best adapted are either large or of severe double curvature or both, and a long period (varying perhaps from 1 to over 10 hours) is required to adjust the strips of veneer in place on or in the

See appendix for partial list of suppliers of glues for bag molding.
mold. During this period, a small amount of hand fitting with a plane or sandpaper block is usually necessary. These conditions require the use of a glue that is dry at the time of assembling and, in general, one that permits an assembly period of at least 30 hours.

It has been suggested previously that the cylinder temperature and pressure be brought up to operating conditions in 5 minutes or less, but in some cases, particularly where large cylinders are used, it is impossible to accomplish this with the available boiler and compressor capacity. Under such conditions there is danger with some glues of precuring the outer glue lines before sufficient pressure is applied. The relation between the characteristics of the glue and the rate of pressure and temperature rise is critical and should be examined carefully.

It is desirable in all bag molding of double-curvature parts with thermosetting glues to use a glue that passes through the fluid stage relatively slow and flows readily while in this stage. This produces the effect of a lubricant between the adjacent plies of veneer and allows them to slip to their proper place, thus often avoiding wrinkles. Most of the glues that are designated as bag-molding glues have this property.

In addition to the characteristics just described, it is important that glues for bag molding be durable under service conditions. The phenolics and certain modified phenolics, melamines, fortified ureas, and thermoplastics meet bag molding requirements reasonably well but vary in their resistance to severe exposure conditions. Current thermoplastic glues, which are otherwise well adapted to bag-molding processes, give evidence of slow flow at subsequent elevated temperatures, such as 150° to 160° F. They are especially adapted to experimental work since they have a high degree of flow when plasticized by the heat in the molding cycle, and if a wrinkle is formed in the molded part, it can often be removed by a subsequent reheating. For molded products that require maximum durability, the phenolic and melamine resin glues are most satisfactory.

**Bag-molding Technique**

**Size, Shape, and Thickness**

In applying bag-molding technique it is necessary to study carefully the piece to be produced. This means a consideration of curvatures, the approximate thickness and number of plies, species, and arrangement of alternate plies. The curvature of the piece may determine the thickness of the veneers that can be used. The following tabulation will serve as a guide to the approximate relation between the thickness of veneer and the minimum radius of curvature considered practical in bag molding:
Approximate minimum ratio of radius of curvature to thickness of dry veneer for bag molding

<table>
<thead>
<tr>
<th>Angle between direction of grain and axis of curvature (Degrees)</th>
<th>Ratio = Radius of curvature / Thickness of veneer</th>
</tr>
</thead>
<tbody>
<tr>
<td>90</td>
<td>100 to 1</td>
</tr>
<tr>
<td>0</td>
<td>50 to 1</td>
</tr>
</tbody>
</table>

These ratios are only suggested minimum values; the actual permissible minimum radius of curvature will vary with the species, type, and moisture content of the veneer. The method of holding the veneer in place on the mold is usually the determining factor; therefore, the suggested ratios are well above those at which the veneer may be expected to break.

Moisture Content

A moisture content of 8 to 12 percent in veneer used for bag molding is favorable, and within this range any variations depend mainly on the glue being used. Variation in moisture content between the veneer sheets in any one assembly should not, however, exceed 2 percent. Change in moisture content during manufacture is often serious, since the veneer strips are cut to exact shape. If the width of the strips changes in the period between shaping and assembly, considerable hand fitting will be required. The importance of dimensional stability depends on the shape and size of the molded part, but in extreme cases on larger parts some plants have found it advisable to control the relative humidity within ± 2 percent in the lay-up room and the rooms where veneer is stored. On other smaller parts or on parts made from narrow strips of veneer no control of average moisture content, other than that required for the glue, is attempted.

The bag-molding operation does not greatly change the moisture content of the veneer, unless leaks develop in the bag. Tests on small flat pieces indicate that the moisture loss during molding is less when using wood molds than when using metal molds. It is also less in both types of molds when no vacuum is maintained on the bag during the curing cycle. Preliminary tests made on plywood molded in bags of suitable grades of cellophane indicate little or no change in moisture content of the veneer during molding when using a steam-air or steam cycle. In all these comparative tests the moisture loss was considerably less in bag molding than in hot-press operations on the same combination of species and glue.
Assembling the Veneer

The degree of double curvature will determine the width of the individual strips of veneer. Naturally it is more economical of labor to use a few wide strips instead of many narrow ones, in order to reduce the number of necessary shaping operations to a minimum. On the other hand, if the strips are too wide, their edges will wrinkle as the fluid pressure on the bag presses the flat strips against the double-curved mold. On double-curvature molds, such as required for aircraft fuselages or boat hulls, the strips are usually between 2 and 8 inches wide.

The strips of veneer must be tapered or "tailored" very carefully to fit the mold so that a close joint is obtained between the adjacent strips. To determine the exact shape of each strip the first lay-up is carefully done by hand and later disassembled, each strip being marked to designate its position on the mold. In production, this tailoring is usually done by first sawing the strips roughly to shape and then shaping them exactly on a vertical spindle shaper, using plywood or metal templates, each accommodating a stack of veneer strips approximately 2 inches high.

Sometimes the pieces are sawed to final shape and then each edge is run through a special scarfing or feathering device consisting of a small sandpaper-lined drum and a hold-down. The strips are then spread with glue and laid on the mold so that the edges overlap 1/4 to 1/2 inch, depending upon the veneer thickness.

As the veneer strips are assembled on the mold, they must be fastened or held in place. On wood molds this fastening is conveniently done by means of staples or tacks. The first layer of veneer is stapled directly to the wood mold and, as each successive layer is applied, the staples in the preceding one are removed. Staples are left in the outer layer of veneer during the molding, and are later removed so that the finished molded piece has no staples in it.

The same principles of balanced construction that apply to flat plywood are applicable to molded plywood. For maximum resistance to warping all plywood should be symmetrical about the central plane of thickness. In this connection symmetry involves species, number of plies, thickness of plies, and direction of grain. In theory, a symmetrically constructed panel with alternate plies laid at 90°, with respect to direction of grain, would have maximum dimensional stability. In practice, however, a construction with alternate plies at 90° to each other is often impossible in pieces of pronounced compound curvature and other angles must be used.

Heating Media

Heating mediums in current use are steam, steam-air mixtures, water, and air. Pure steam is often used when high temperatures are desired. In this cycle an exhaust valve is left partly open for a short period after the steam valve is opened so that the residual air is expelled.
The steam-air mixture usually requires an air compressor in addition to a steam boiler. Some so-called steam cycles are in effect steam-air cycles as the cylinder is sealed and charged with steam without discharging the residual air. Under these conditions the temperature and pressure of the charge will not agree with temperature-pressure tables for pure saturated steam.

For economy in operation the air required in a steam-air mixture should be injected first, followed by the steam to produce the desired temperature and pressure. The amount of air pressure at room temperature required for any cycle can be approximated by calculation if desired. For example, assume that a molding cycle of 75 pounds per square inch at 275° F. is required. From steam tables, 275° F. requires a gage pressure of approximately 31 pounds per square inch. The remainder of the cylinder pressure, or 75 - 31 = 44 pounds per square inch, must be supplied by air. If this air is injected first at room temperature, or approximately 75° F., and later heated by the steam, its pressure is increased. The air pressure required at 75° F. can be calculated from the formula:

\[ P_0 = P_1 \times \frac{T_0}{T_1} \]

where \( P_0 \) = absolute air pressure at 75° F., \( P_1 \) = absolute air pressure at 275° F. (44 + 14.7 = 58.7 p.s.i.), \( T_0 \) = absolute temperature of unheated air or 75 + 460 = 535° F., and \( T_1 \) = absolute temperature of heated air or 275 + 460 = 735° F.

\[ P_0 = 58.7 \times \frac{535}{735} = 42.7 \text{ p.s.i. (abs.)} \]

\[ 42.7 - 14.7 = 28.0 \text{ p.s.i. (gage pressure)} \]

The gage pressure of air required at 75° is 28 p.s.i.

The use of hot water requires an auxiliary storage tank in which the water is heated and to which it is returned after use in the heating cycle. This tank is often mounted above the molding cylinder so that the hot water can be introduced rapidly by gravity through a large pipe. It is returned by means of a centrifugal pump. The pressure for the molding operation is applied by air.

When air is used as a pressure and heating medium, heating may be done by means of a steam jacket around the cylinder. Heat is sometimes supplied by steam coils within the cylinder or possibly by electric strip heaters. Extreme caution should be exercised when using electric heaters or any electric connection inside the cylinder, as the combination of compressed hot air, combustible material, and a glowing heater within a cylinder is very dangerous. In planning such an operation, all known safety precautions and regulations should be observed. The compressor should always be equipped with an adequate aftercooler and oil-vapor filter. The lubricating oil in
the compressor should have a high flashpoint so that a minimum of vapor is
given off. All precautions should be taken to eliminate any sparks in a
cylinder charged with hot air containing some oil vapor, as a dangerous
explosion can result.

Each heating medium has certain practical limits of temperature. An attempt
has been made at the Forest Products Laboratory to determine these limits
from actual heating tests in which thermocouples were inserted in the
cylinder and at various depths in a piece being formed on a wood mold to
record the rise in temperature. These limits as well as other practical
limitations of 14 different techniques which have been or could be used in
bag molding plywood are presented in table I.

Hot air is a very slow heating medium and, in addition, produces results
very largely dependent upon the amount of circulation in the cylinder. There
is considerable interest, however, in the use of air, for two reasons:
first, leaks developing in bags do not damage the piece and the mold, as is
likely with the steam or hot-water cycle; and, second, a few of the bag
materials suggested as substitutes for rubber are not steam- or hot-water
proof but are adapted for use with air or some inert gas.

Amount of Pressure

The pressures used in bag molding vary from a vacuum drawn on the bag
(atmospheric pressure or less) to a maximum of about 120 pounds gage pres-
sure per square inch. Most current bag molding is being done at pressures
from 40 to 80 pounds per square inch. Vacuum alone produces insufficient
pressure for most bag-molding operations and therefore is not recommended
for critical work.

Heating Cycle

The selection of a proper heating cycle to cure the glue and bond the
veneer into the finished molded part is complicated by the fact that the
synthetic resins do not have a definite temperature at which polymerization,
or condensation, occurs.

For example, a phenolic-resin film is reported to be completely cured in
about 1/2 minute at 350° F. but requires about 10 minutes at 275° F. This
suggests the development of fundamental temperature-time relationship
factors for accurately calculating the time required to cure completely
each of the common synthetic-resin glues but, for the present, the heating
cycle can only be determined empirically.

It is necessary to maintain a uniform temperature in the cylinder throughout
the cycle and avoid stratification of the heating medium by means of adequate
circulation in the cylinder to secure uniform rates of heating.

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Under any particular set of operating conditions, an occasional check of the actual temperature at the coolest glue line throughout the heating cycle is desirable. A satisfactory method of making this check is to use fine thermocouples and a potentiometer. Copper and constantan thermocouples of No. 30 gage wire have been found satisfactory and may be embedded in the molded part without danger of injuring trimming equipment. Approximate temperature checks have also been made in some cases by the use of temperature-sensitive crayons or paints. The final check, of course, is the ability of the glue joints in the finished product to meet specification requirements.
APPENDIX

Partial List of Manufacturers of Rubber Bag Materials or Bags

1. E. I. duPont deNemours & Co., Inc., Fabrikoid Division, Fairfield, Conn.
4. B. F. Goodrich Co., 450 S. Main St., Akron, Ohio.

Partial List of Suppliers of Bag-molding Glues

American Cyanamid Co.
Plastics Div.
30 Rockefeller Plaza
New York City

Bakelite Corp.
230 Grove St.
Bloomfield, N. J.

Carbide & Carbon Chemicals Corp.
30 E. 42nd St.
New York City

Casein Co. of America
Bainbridge, N. Y.

Catalin Corp.
1 Park Ave.
New York City

E. I. duPont deNemours & Co.
Plastics Dept.
Arlington, N. J.

Dures Plastics & Chemicals, Inc.
1181 Valck Road
North Tonawanda, New York

Lauxite Corp.
Lockport, N. Y.

Monsanto Chemical Co.
Plastics Div.
Springfield, Mass.

Perkins Glue Co.
Lansdale, Pa.

Plaskon Co., Inc.
2112-24 Sylvan Ave.
Toledo, Ohio

Resinous Products & Chemical Co.
222 W. Washington Sq.

Shawinigan Products Corp.
350 Fifth Ave.
New York City
Partial List of References on Fluid-pressure-molded Plywood

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(3) How to apply rapid, large scale production technique to making moulded plywood fuel tanks. Wood Prod. 49(12): 18-21, 67, illus. December 1944.


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HEMMING, C. B.

LUDERS, A. E.

MARHONER, L. J.

MILLER, E.

MOON, H. P.

NEBESAR, R. J.

PACIFIC VENEER COMPANY, LIMITED.

RESINOUS PRODUCTS AND CHEMICAL COMPANY.

U. S. FOREST SERVICE, FOREST PRODUCTS LABORATORY.
Chapter 5.3. Bag-molded plywood and structures, p.229-249.

U. S. NAVY DEPT. BUREAU OF AERONAUTICS.

Report No. R1624 -18-
Partial List of Patents on Fluid-pressure Molded Plywood

(1) ALLWARD, G. A.  
1942. AIRCRAFT WING STRUCTURE. (U. S. Patent No. 2,273,919)

(2) REASECKER, R. L.  
1945. APPARATUS FOR FABRICATING PLYWOOD STRUCTURES. (U. S. Patent No. 2,380,573)

(3) REASECKER, R. L.  
1943. CONTAINER FOR ASSEMBLIES TO BE BONDED. (U. S. Patent No. 2,307,936)

(4) WENDRIS, VINCENT  
1945. VENEER PRESS. (U. S. Patent No. 2,390,684)

(5) CLARK, V. E.  
1941. AIRCRAFT WING STRUCTURE. (U. S. Patent No. 2,258,134)

(6) PUNCTER, J. A. and BASKIN, C. H.  
1943. APPARATUS FOR MANUFACTURING LAMINATED MATERIAL. (U. S. Patent No. 2,308,453)

(7) TEAGUE, M. M.  
1937. FLUID PRESSURE VENEER PRESS. (U. S. Patent No. 2,073,290)

(8) THAYER, H. V.  
1945. APPARATUS FOR PRODUCING LAMINATED STRUCTURES. (U. S. Patent No. 2,362,227)

(9) VENNER, WILLIAM  
1940. METHOD OF MAKING PLYWOOD SHELLS. (U. S. Patent No. 2,223,587)

(10) VIDAL, E. L.  
1944. METHOD OF FORMING LAMINATED MOLDED STRUCTURES. (U. S. Patent No. 2,342,988)

(11) VIDAL, E. L. and MARHOEFER, L. J.  
1942. METHOD OF FORMING VENEER STRUCTURES. (U. S. Patent No. 2,276,004)

(12) VIDAL, E. L. and MARHOEFER, L. J.  
1946. METHOD OF FORMING LAMINATED STRUCTURES. (U. S. Patent No. 2,394,730)

(13) VIDAL, E. L. and TAYLOR, W. A.  
1946. APPARATUS FOR MOLDING LAMINATED STRUCTURES. (U. S. Patent No. 2,388,108)
Figure 1.--Five methods of forming bag-molded plywood.
Figure 2.—Metal bleeder connection designed for rapid attachment to bags.
Table 1: Equipment and limitations on conditions in various methods of bag-molding plywood

<table>
<thead>
<tr>
<th>Table 1: Illustrated</th>
<th>Major equipment required</th>
<th>Pressure</th>
<th>Source of heat</th>
<th>Practical: Practical limits of materials:temperature</th>
<th>Practical: limits of pressure</th>
<th>Mold material</th>
</tr>
</thead>
<tbody>
<tr>
<td>C and E</td>
<td>Autoclave, boiler, air compressor</td>
<td>Steam-air</td>
<td>120 to 140</td>
<td>120 to SWP 2</td>
<td>Metal  or plastic or cement or wood</td>
<td>Wood, metal, or plastic or cement or wood</td>
</tr>
<tr>
<td>A</td>
<td>Vacuum pump, radiant heater</td>
<td>Steam-air</td>
<td>120 to 140</td>
<td>120 to SWP 2</td>
<td>Metal  or plastic or cement or wood</td>
<td>Wood, metal, or plastic or cement or wood</td>
</tr>
<tr>
<td>A</td>
<td>Vacuum pump, boiler or electric heater</td>
<td>Steam</td>
<td>120 to 140</td>
<td>120 to SWP 2</td>
<td>Metal  or plastic or cement or wood</td>
<td>Wood, metal, or plastic or cement or wood</td>
</tr>
</tbody>
</table>

| Class 1 — Steam-, water-, and air-tight at temperatures up to 320°F. Natural and synthetic rubber and some grades of cellulose. |
| Class 2 — Air-tight and usable up to a temperature of 320°F. — cellulose. |
| Class 3 — Air- or liquid-tight up to a temperature of 212°F. — rubber, cellulose, resin-coated cloth, and thermoplastic films. |

SWP equals the safe working pressure of the apparatus being used, which is determined by the type and condition of the apparatus and State safety code requirements.

A mold that will withstand internal fluid pressure.
Notes Referring to Table 1

1. Natural and synthetic rubber give highest production bag life with pure steam; some grades of cellophane are usable for one cycle. Pressure is too low for general bag-gluing below 260°F (20 lb. per sq. in. at 260°F); above 320°F there is danger of overcuring the outer glue joint and bag deterioration is very rapid.

2. Steam-air is more damaging to rubber than steam or hot water; some grades of cellophane are usable for one cycle. Circulation to avoid stratification is sometimes required, especially below 240°F; rapid oxidation of bag materials occurs above 300°F.

3. Long bag life can be expected from hot water cycle as there is very little oxidation; some grades of cellophane are usable for one cycle. Open-storage tank may be used below 212°F; above 300°F pure steam can ordinarily be used to advantage since the water must be kept under the same pressure as is required for steam.

4. This is a very slow cycle due to low specific heat of air. Seventy-five lb. per sq. in. is suggested as maximum safe pressure. Precautions should be taken to avoid oil vapor from compressor and static discharges from circulating fan.

5. Carbon dioxide, nitrogen, or any other gas which will not support combustion or affect bag materials should be used. Do not use air as there is danger of exothermic reaction or explosion.

6. Mold is heated, and unheated air is used for pressure; therefore bag stays relatively cool throughout cycle.

7. Same as 6, except that inert gas is recommended to avoid danger of explosion in case of spark or a short circuit in wiring system.

8. Bag is expanded against work by means of steam. An adequate drain for condensate is required at the lowest spot in the bag.

9. Same as 8, except that steam-air mixture is used. See note 2.

10. Steam-heated mold is used; bag inflated by air pressure, therefore no drain connection necessary for bag.

11. Same as 10 except that mold is heated electrically; inert gas is recommended for safety, although air may be used.
12. Radiant heat is applied to the outside of a bag collapsed on the mold. Satisfactory bonds are obtainable at vacuum-induced pressure with certain hot-setting glues. Parts must be flat or of slight curvature.

13. Same as 12, except that mold is heated by steam or electricity.

14. Same as 12, except that evacuated bag containing work is submerged in a hot liquid to supply heat. With water, temperature is limited to 212° F. Hot oil or some other high-boiling point liquid possibly can be used with bag materials such as cellophane or resin-coated fabric.