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ATTEMPT TO PRODUCE FLEXIBLE PLYWOOD WITH USE OF EUROPE WOOD SPECIES

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ABSTRACT

The present study investigates the possibility of producing flexible plywood glued with UF resin with use of wood species typical for plywood industry, such as birch, beech, alder, pine, linden, poplar, willow and spruce. An important part of the study was also to find out whether it is the material factor or the specific structure that mostly affects the properties related to the flexibility of the material. The investigations have led to the conclusion that the optimum material for the core veneer of plywood is pine, and the best elastic properties are attained for plywood with face veneers made from poplar, birch and linden. When other properties are taken into consideration, poplar plywood turns out to be the most similar to the typical flexible plywood.

KEYWORDS: Flexible plywood, properties of plywood, wood species.

INTRODUCTION

At present, flexible plywood in many areas is competitive to other materials used in the production of curvilinear items. In comparison with other materials, flexible plywood is characterized by user-friendliness, since no special equipment is necessary to form the curvilinear items. Moreover, there is no need to use skeleton constructions while preparing profiles. The designed forms can be promptly assembled, as opposed to works connected with postforming, characteristic of other materials. By manufacturing goods with use of flexible plywood it is possible to save time and increase the production efficiency. What is more, flexible plywood has all the advantages of traditional plywood. Flexures made with use of flexible plywood are characterized by even and smooth surface; the plywood can be easily milled, it shows good connectivity, and after final fixing it remains stiff. Good qualities of this product lead to the increase in its production and use. It is suitable for curvilinear furniture items, stairs and handrails, interior design. Due to its little weight and treatment facility, flexible plywood can be used to make oval structures of ceilings, walls and pillars. It is used as a covering material in yacht and boat constructing and, also, in the production of toys and fancy goods. There are two major sources of good properties of flexible plywood: Its specific structure and the fact that only wood with precisely specified properties is used in its production. It is manufactured as three or five-layer plywood with face veneers considerably thicker that the core veneer. In the core layer, the applied veneers are 0.8-m-thick, made from long fibre wood species with medium density and high values of bending strength. The face veneers are made from wood species with thin-walled cells, so that it is easier to squeeze the plywood from one side and stretch it from the other. Therefore, only the wood species that can meet those requirements are used in the manufacturing process, i.e. selected deciduous and exotic wood species, such as gaboon (okoume), ceiba (fuma). Sometimes, the type of resin is also taken into consideration in the production of flexible plywood (Oka and Yamashita 1991; Borysiuk et al. 2007). However, the use of exotic wood species makes the production of flexible plywood very expensive. Its price is much higher than the price of e.g. molded plywood, which is an expensive material in itself. A direct comparison of the properties of exotic and other wood species shows that the latter have more disadvantages. Nevertheless, researchers work on introducing those species into the plywood production since it would considerably reduce manufacturing costs and expand the material resources (Borysiuk et al. 2003; Kaiser 2003; Borysiuk et al. 2007). That is why, for many years investigations have been carried out aiming at substituting wood, which is used in the production of wood-based materials (particleboards, fibreboards), with annual plants form different regions of the world, such as flax and hemp shives, bagasse, jute, cotton stems, grasses, oat glumes, straw of the four staple cereals and alternative plants (Girgoriou 2000; Mo et al. 2003; Boquillon et al. 2004; Guler and Ozen, 2004; Czarnecki and Dukarska 2010; Dukarska et al. 2010; 2011). Some authors considered also applying wood of different species or of inferior quality, other than those commonly used in the industry. The investigations prove that species such as aspen, robinia, willow, birch, ash, linden, elm can be also used in the production of particleboards, fibreboards and OSB (Chow and Zhao 1992; Güller and Nurgül 2001; Nemli, 2003; Barbuta et al. 2011; Mirski and Dziurka 2011a, 2011b; Rathke et al. 2012; Kowaluk et al. 2013).

The aim of the present research project was to determine the possibility of producing flexible plywood with use of wood species that are typical for the plywood industry. It was also important to state whether it is the material factor or the specific structure that mostly affect the properties which determine the elasticity of the material. It was also significant to find out whether it is possible to produce flexible plywood without introducing essential modifications to the production process. That is why, the all the investigations were carried out in industrial conditions.

MATERIAL AND METHODS

For the research purposes, we selected the following wood species: Alder (*Alnus glutinosa* Gaertn.), birch (*Betula pendula* Roth), beech (*Fagus sylvatica* L.), pine (*Pinus sylvestris* L.), linden (*Tilia cordata* Mill.), poplar (*Populus alba* L.), willow (*Salix alba* L.), spruce (*Picea abies* L.). Alder, birch, beech and pine are typical wood species widely used in the veneer industry. We applied the following conditions of hydrothermal treatment of the material for plywood: The temperature of steaming wood was 80-90°C, the time of steaming wood was 0.8 h per 1 cm radius for alder and birch, 2.0 h per 1 cm radius for beech and 0.6 h per 1 cm radius for pine, linden, poplar, willow, spruce. The moisture content of the veneers was 4-6 %. In order to determine the applicability of veneers of the tested wood species, we determined properties such as bending strength and modulus of elasticity in bending parallel to the grain for the veneers peeled to the thickness of 1.7 mm. Depending on the pressing variant, we used veneers with thickness of 0.8, 1.0, 1.4, 1.7 and 2.4 mm. Equilibrium moisture content of veneers reached the level of 4-6 %. In the course of the investigations, urea-formaldehyde resin (UF) was used. The physical and chemical properties of UF resin were as follows: Dry mass content – 66 %, miscibility with water – min. 0.8 $cm^3.g^{-1}$, gel time – max. 70 s, viscosity – 1.295 ± 0.015 $g.cm^{-3}$, pH 8.0 ÷ 9.0 and free formaldehyde content – max. 0.2 %. In order to catalyze the cross-linking process of the resin, we applied a curing agent: 20 % ammonium salt aqueous solution, non-chloriniferous, including formaldehyde catchers. As a filler for this resin we used rye flour. The resin load was 140 $g.m^{-2}$ and it was made on the basis of technological conditions. In the course of the research, we manufactured three-layer plywood. The particular variants differed in the type of wood and veneer thickness. Other pressing parameters did not change. The press pressure and temperature were 1.4 $N.mm^{-2}$ and 105ºC respectively, for 5 min of pressing time. After the pressing, the plywood was seasoned for 72 hours. At that time the moisture content reached the level of 7-8 %. We made an assumption that the first variant of the pressed plywood would be made entirely from the same type of wood, and the standard thickness of veneer, i.e. 1.7 mm would be applied. Then, as the following variants were produced, the veneer thickness changed gradually, according to the rule that, in case of flexible plywood, the core veneer is thinner than the face veneers. Therefore, we were going to find out how the specific structure of flexible plywood affects the properties of the manufactured material, especially its elasticity. If any observations and results, which appeared in the course of the research, indicated that there was a need to modify the consecutive variants, we made the necessary alterations as for the variable parameters.

In variant 1, we used in the process all the wood species suggested for investigation, and the veneer thickness was 1.7 mm. The material obtained for the research purposes was entirely made from veneer of the following species: Alder, birch, beech, pine, linden, poplar, spruce and willow. The determined properties of this variant of plywood were the point of reference for the other variants. Variant 2 was an attempt to produce such a material whose properties would be more similar to those of flexible plywood with thickness of 3 mm. The core veneer was supposed to be made from pine wood, as only selected coniferous wood species partially meet the requirements for the core veneer: Long fibre wood with medium density and high bending strength. Considering all the available wood species used in the production of plywood, only pine wood could be taken into account. The face veneers were made from the other wood types selected for the research, i.e. birch, beech, alder, willow, poplar, linden and spruce. The core veneer was 1.0 mm thick, and the thickness of face veneers was 1.4 mm.

In variant 3, we rejected beech veneer due to its high density. The core veneer was made from pine veneer with thickness of 0.8 mm, and the face veneers were made from birch, alder, linden, poplar, spruce and willow with thickness of 2.4 mm. From the point of view of its structure, variant 3 strictly followed the rules of producing flexible plywood. As a comparison material for the produced plywood, we applied the typical flexible plywood for use in dry conditions with thickness of 5 mm. After conditioning, we subjected the manufactured plywood to analyses of bending strength (MOR) and modulus of elasticity in bending (MOE) parallel (II) and perpendicular (⊥) to the grain in face veneers according to EN 310 (1993), and tensile strength (TS) according to EN 789 (2004).

The produced plywood was tested in terms of bond quality by the assessment of shear strength of glue line and shear failure in wood after water resistance tests according to standard EN 314-1 (2004). We determined the formaldehyde emission with the gas analysis method according to EN 717-2 (1995). In order to obtain results which could serve as a point of reference for plywood produced in variants 1, 2 and 3, we subjected the typical flexible plywood with thickness of 5 mm to the same tests. Additionally, we used a non-standard method to determine the flexible properties of plywood produced according to variant 3 and the typical flexible plywood with thickness of 3 and 5 mm. Especially for the purposes of the research, we developed a method of determining the elastic properties of plywood: Specimens of plywood with the dimension of 50 x 200 mm were bent on wooden rollers with various diameters: 30, 40, 50, 60, 70, 80, 100, 120 and 140 mm.; it was a test made in the-across-the-grain direction. At the first stage, we determined the diameter at which a specimen cracked: The test started with the 140 mm roller and, one by one, rollers of smaller diameters were checked. At the other stage of the investigations, three specimens were used. This time, however, the tests started with a larger diameter than that determined at the initial stage. The reaction of the specimens was presented in a descriptive manner.

RESULTS

Properties of veneers produced from all the investigated wood species

An attempt to find the optimal properties of veneers means indicating wood species that can be applied as the core and face veneers. For the first criterion (core veneer), long-fibre wood with high value of internal bond and medium density is needed. The highest values of internal bond were obtained by birch, pine, beech and alder (Tab. 1). Having considered the values of density and structure, it is pine that best meets the requirements for the core, which in fact confirms the preliminary assumptions made in the methodology. The best species for the face layers are those of thin-walled cells, low density and high elasticity values. None of the investigated wood species meets the first criterion, and the species with the highest elasticity are poplar, linden, willow and spruce. The last one, however, may cause certain problems due to its density and the presence of numerous hard knots. Therefore, it is poplar, linden and willow that seem the most suitable types of wood.

Tab. 1: Results of investigation upon properties of veneers.

Wood species	MOR (II)	MOE (II)
	(N.mm^{-2})	
Birch	144.2 (11.3)*	12 600 (2460)
Beech	126.6 (3.8)	10 150 (1150)
Alder	121.3 (4.0)	12 600 (1170)
Pine	127.1 (9.6)	14 770 (1420)
Linden	80.6 (3.2)	6 470 (720)
Spruce	72.3 (4.1)	7 610 (880)
Poplar	69.0 (3.1)	5 950 (640)
Willow	78.7 (3.2)	6 950 (780)

* – standard deviation

Properties of plywood produced according to variant 1

According to the Standard EN 314-2 2008, the research results are evaluated on the basis of the obtained values of shear strength of the adhesive-bonded joint and shear failure in wood. However, when the values are higher than 1.0 N.mm^{-2}, the analysis of shear failure in wood is less important. Mean values of shear strength of plywood tested after 24 h soaking test considerably exceeded the value of 1.0 N.mm^{-2}, which classified all the manufactured plywood (variant 1, 2 and 3) to bonding grade 1, typical of plywood used in dry applications. The f_v values are obtained within the range of 2.0 – 3.0 N.mm^{-2}. Tabs. 2–5 present properties of typical plywood made from all the investigated wood species. The results shown in Tabs. 2 and 3 should be regarded as typical of plywood made from the investigated wood species. As for modulus of elasticity in bending in the across-the-grain direction (class E5 according to the Standard EN 636 2012), the lowest values that are acceptable for traditional plywood were achieved by plywood produced from pine, poplar and willow. Elasticity values below the standard of E5 class would make this material inconsistent with all the technical requirements for the traditional plywood. Therefore, the properties of plywood made from pine, poplar and willow wood are close to those of flexible plywood. The results of investigations upon tensile strength presented in Tab. 3 should be considered very typical of plywood made from the investigated wood species. In general, the highest values of tensile strength were observed in case of beech and linden plywood. The worst results were obtained for spruce plywood. The values achieved for the other investigated species were much the same.

Tab. 2: Bending strength and modulus of elasticity in bending of plywood produced according to variant 1.

Type of plywood	Density	MOR (II)	MOE (II)	MOR (⊥)	MOE (⊥)
	(kg.m^{-3})	(N.mm^{-2})			
Birch	610	121.7 (7.0)*	13 180 (990)	27.1 (2.1)	1 140 (110)
Beech	760	159.8 (7.2)	19 350 (920)	32.9 (2.2)	1 420 (120)
Alder	570	112.1 (3.7)	12 520 (290)	21.6 (0.9)	940 (50)
Pine	590	91.2 (9.8)	10 420 (143)	21.4 (2.3)	970 (100)
Linden	620	106.3 (5.6)	12 920 (910)	24.2 (2.1)	1 090 (120)
Spruce	560	103.5 (6.6)	9 800 (760)	17.7 (2.9)	870 (160)
Poplar	560	117.1 (5.8)	10 630 (440)	23.0 (1.8)	870 (50)
Willow	610	103.6 (4.1)	9 130 (460)	22.9 (1.7)	940 (90)

* – standard deviation

Tab. 3: Tensile strength of plywood produced according to variant 1.

Type of plywood	TS (N.mm^{-2})		
	At the angle of 45°	Parallel to grain	Across the grain
Birch	24.6 (2.4)*	65.5 (6.2)	49.9 (3.7)
Beech	20.6 (3.3)	104.6 (6.2)	52.6 (3.3)
Alder	21.7 (3.1)	70.2 (8.2)	42.0 (3.9)
Pine	14.1 (1.2)	72.9 (4.1)	30.5 (2.9)
Linden	25.3 (1.5)	93.7 (5.7)	51.9 (3.4)
Spruce	25.5 (3.4)	54.6 (6.8)	24.1 (2.9)
Poplar	20.8 (1.2)	78.7 (7.6)	38.8 (3.4)
Willow	29.3 (1.7)	71.9 (6.5)	35.5 (3.2)

* – standard deviation

Properties of plywood produced according to variant 2

Tabs. 4 and 5 present properties of plywood manufactured from pine core layer with thickness of 1.0 mm and from two 1.4-mm-thick face layers made from birch, beech, alder, spruce, willow, poplar and linden. The change in the structure of plywood resulted in a considerable decrease in bending strength in the across-the-grain direction in case of birch, beech and alder plywood (the effect of substituting pine for the core veneer). For all the investigated wood species, a very significant decrease in the value of modulus of elasticity in bending in across-the-grain direction was observed. The values of modulus of elasticity in bending for poplar and linden plywood were lower than the requirements of E5 class according to Standard EN 636 2012, and willow plywood merely touched the required values of this class. The changes of the plywood structure improved its elastic properties, still indicating that the optimum material for face layers are linden, poplar and willow. A great majority of the results shown in Tab. 4 are lower that the respective results presented in Tab. 2. This trend was also observed in the case of measuring the tensile strength (Tabs. 3 and 5).

Tab. 4: Bending strength and modulus of elasticity in bending of plywood produced according to variant 2.

Type of plywood	Density ($kg.m^{-3}$)	MOR (II) ($N.mm^{-2}$)	MOE (II)	MOR (⊥)	MOE (⊥)
Birch	660	126.1 (4.7)*	12 450 (450)	17.1 (2.1)	820 (120)
Beech	720	163.1 (9.1)	15 150 (920)	14.6 (1.9)	890 (110)
Alder	530	100.6 (4.9)	10 200 (440)	17.7 (1.8)	780 (90)
Linden	760	120.6 (5.1)	14 160 (540)	11.5 (1.3)	500 (70)
Spruce	570	114.1 (5.2)	13 840 (870)	12.9 (1.6)	490 (80)
Poplar	570	94.8 (3.8)	10 350 (580)	16.3 (1.1)	660 (40)
Willow	620	79.3 (2.1)	8 450 (240)	12.3 (0.7)	510 (60)

* – standard deviation

Tab. 5: Tensile strength of plywood produced according variant 2.

Type of plywood	TS ($N.mm^{-2}$) At the angle of 45°	Parallel to grain	Across the grain
Birch	25.4 (2.8)*	96.7 (6.8)	28.9 (1.9)
Beech	24.2 (2.6)	104.1 (5.8)	27.4 (2.1)
Alder	23.0 (1.9)	59.1 (4.2)	21.6 (1.7)
Linden	19.5 (1.3)	81.0 (4.8)	32.6 (1.6)
Spruce	17.0 (1.0)	54.1 (2.8)	23.1 (1.6)
Poplar	21.8 (1.4)	54.4 (3.8)	23.2 (1.6)
Willow	21.2 (0.9)	63.7 (3.9)	13.5 (1.2)

* – standard deviation

It is due to the fact that the core layer is made from pine wood, which as other coniferous species is characterized by low values of tensile strength in across-the-grain direction.

Properties of plywood produced according to variant 3

Tabs. 6 and 7 present properties of plywood manufactured from pine core layer with thickness of 0.8 mm and from two 2.4-mm-thick face layers made from birch, alder, willow, spruce, poplar and linden. Respective results obtained for the typical flexible plywood made from exotic wood species are shown in Tab. 8. The measurement results of the deflection radius for plywood produced according to variant 3 are shown in Tab. 9. The increase in the proportion between the thickness of the face veneers and the core veneer results in a decrease in the modulus of elasticity in bending in the across-the-grain direction. Apart from alder plywood, all the other types were characterized by lower values of this property than the class E5 requirements according to EN 636 2012; in case of poplar plywood also the modulus of elasticity in bending in the across-the-grain direction is relatively low.

Tab. 6: Bending strength and modulus of elasticity in bending of plywood produced according to variant 3.

Type of plywood	Density (kg.m^{-3})	MOR (II)	MOE (II)	MOR (⊥)	MOE (⊥)
		(N.mm^{-2})			
Birch	690	118.3 (5.1)*	14 490 (620)	7.5 (0.3)	300 (30)
Alder	580	98.5 (4.6)	12 950 (590)	9.6 (0.5)	520 (40)
Linden	580	112.0 (5.0)	12 550 (520)	7.7 (0.3)	250 (20)
Spruce	510	119.3 (5.5)	12 870 (630)	7.6 (0.4)	250 (20)
Poplar	490	76.6 (3.4)	7 600 (320)	7.0 (0.3)	290 (20)
Willow	480	93.0 (4.2)	10 150 (490)	7.7 (0.3)	260 (20)

* – standard deviation

Tab. 7: Tensile strength of plywood produced according to variant 3.

Type of plywood	TS (N.mm^{-2})		
	At the angle of 45°	Parallel to grain	Across the grain
Birch	15.2 (1.1)*	60.3 (4.2)	17.1 (1.3)
Alder	14.2 (1.2)	53.8 (2.7)	15.6 (0.9)
Linden	13.1 (0.8)	72.9 (3.6)	11.8 (0.5)
Spruce	8.6 (0.6)	51.5 (2.8)	10.7 (0.8)
Poplar	15.4 (0.8)	51.6 (2.3)	11.2 (0.5)
Willow	9.9 (0.5)	54.5 (2.5)	12.1 (0.5)

* – standard deviation

For the traditional plywood (variant 1), bending tests even in the across-the-grain direction provided poor results and it was in fact impossible to apply the described method of production. What is more, in spite of a considerable increase in the elasticity of the plywood produced according to variant 2, also in this case this manufacturing method could not be used. Only variant 3 can be regarded as suitable for this kind of test. The descriptive results are presented in Tab. 9. The worst values of deflection radius were obtained in case of spruce, alder and willow plywood. Much better results were achieved by birch and linden plywood.

Tab. 8: Properties of the typical flexible plywood for use in dry conditions.

MOR (II)	MOE (II)	MOR (⊥)	MOE (⊥)	TS		
				at the angle of 45°	parallel to grain	across the grain
(N.mm^{-2})						
46.1 (2.2)*	4 370 (200)	3.3 (0.2)	80 (10)	9.5 (0.5)	31.4 (1.4)	16.5 (0.8)

* – standard deviation

Tab. 9: Deflection radius of plywood produced from selected wood species.

Type of plywood	Roller with the diameter of		
	100 mm	120 mm	140 mm
Alder	Specimens fractured	Specimens bent, yet the face layers partially cracked	Specimens bent with no sign of damage
Birch	Specimens bent, yet the face layers partially cracked	Specimens bent with no sign of damage	Specimens bent with no sign of damage
Linden	Specimens bent, yet the face layers partially cracked	Specimens bent with no sign of damage	Specimens bent with no sign of damage
Poplar	Specimens bent, yet the face layers partially cracked	Specimens bent with no sign of damage	Specimens bent with no sign of damage
Spruce	Specimens fractured	Specimens fractured	Specimens bent, yet the face layers partially cracked
Willow	Specimens fractured	Specimens bent, yet the face layers partially cracked	Specimens bent with no sign of damage

The best values were obtained for poplar plywood; yet, this type of plywood was also the thinnest. Therefore, we can make a conclusion that for birch, linden and poplar plywood the deflection radius amounts to 100 mm. For the typical 5-mm-thick flexible plywood with density 380 $kg.m^{-3}$, investigated with use of the same method, the value of deflection radius was 50 – 60 mm. Flexible plywood made from the selected wood species does not have such good flexural properties as the typical flexible plywood. Nevertheless, the obtained results seem interesting also due to the fact that the other investigated properties are not much different from those of traditional plywood, as opposed to properties of the typical flexible plywood.

In case of plywood, the results obtained by means of gas analysis up to the value 5 mg CH_2O $m^{-2}.h^{-1}$ meet the requirements of E1 emission class. Here, all the measurement results have considerably lower values and amount to 0.75 – 2.69 mg CH_2O $m^{-2}.h^{-1}$.

DISCUSSION

The production of flexible plywood actually means producing a material of entirely different properties that those of traditional plywood. As far as bending strength is concerned, the best wood species to be used as the core veneer of flexible plywood are birch, pine, beech and alder. However, when other properties, such as density and length of fibres, are taken into account, pine is the optimum material; it is also confirmed by investigations by Borysiuk et al. (2003). When density and modulus of elasticity in bending are taken into consideration, the best wood species for face veneers are poplar, linden, willow and spruce. The investigations on the deflection radius of the produced plywood show that the best elastic properties are observed for plywood produced according to variant 3, i.e. plywood with 2.4-mm-thick face veneers made from poplar, birch and linden and with the core veneer made from pine with thickness of 0.8 mm. For these species, 120 mm deflection radius was attained, whereas in the investigations by Borysiuk et al. (2007) for plywood produced with use of 0.8-mm-thick core veneers made from pine, and 3-mm-thick face veneers made from aspen and birch, the obtained values for deflection radius amounted to, respectively, 200 and 250 mm. In that case, the density of the produced plywood was similar, yet the values of bending strength and modulus of elasticity in bending in the across-the-grain direction were higher. As the value of the face veneers thickness/core veneer thickness coefficient grows, the elasticity of the product increases. The value of the coefficient in the investigated plywood raises from 1 in the variant 1 up to 6 in the variant 3; it is also accompanied by a decrease in bending strength and modulus of elasticity in bending. Plywood produced according to variants 1 and 2 did not show any properties that would make it possible to attain sufficient elasticity. If the density of the product is taken into account, it is poplar plywood produced according to variant 3 that shows properties that are similar to those of typical flexible plywood: It has the lowest density, i.e. 490 kg.m^{-3}, and the lowest values of bending strength and modulus of elasticity.

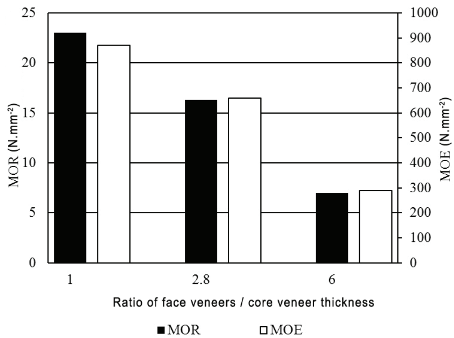

Fig. 1: Changes in the elasticity of poplar plywood depending on the ratio of face veneers and core veneer thickness.

Fig. 1 shows changes in the elasticity of poplar plywood depending on the ratio of face veneers and core veneer thickness. The investigations show also that flexible plywood made from the selected wood species retains other good properties, such as high quality of glue bond and higher value of internal bond determined at the angle of 45º or in the parallel-to-grain direction. Therefore, it is possible to produce plywood with increased flexibility from wood species which are used not only in the production of traditional plywood but also those which have not been considered much useful so far. The presented findings can become a foundation for further investigations in this area, especially aimed at determining the optimum structure and manufacturing conditions for this kind of plywood.

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