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BONDING TECHNOLOGY OF ELECTROMAGNETIC SHIELDING PLYWOOD LAMINATED WITH CONDUCTIVE SHEETS

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ABSTRACT

Radiations from different electrical devices cause electromagnetic interference which will influence the performance realization of other electromagnetic device and cause the health concerns. The conductive sheets were then used to develop wood electromagnetic shielding plywood by laminating with the wood veneers. The shielding effectiveness of plywood ranged from 55.87 to 71.75 dB (100 KHz to 1 GHz) which indicated it could be used as effective shielding materials for electromagnetic radiation. Through analyzing on the bonding method in the design of electromagnetic compatibility structure and considering the characteristics of electromagnetic shielding plywood for engineering applications, the bonding methods were designed into opposite joint by glue, inclined joint by glue and step joint by copper foil. The shielding properties of plywood after bonding were evaluated using two methods. The results showed that the seams between the joint plywood resulted in the decline of electromagnetic performance. From the coaxial test, it was found that this test method could not be effectively evaluated the bonding quality when the joint seams were located in the diameter direction of the annular specimen. From the shielding room test, the shielding effectiveness descent of plywood using copper foil connection method decreased smaller than that of the other two connecting methods, which indicated that the copper foil connection was the best bonding method to suppress the electromagnetic leakage.

KEYWORDS: Conductive sheet, electromagnetic shielding plywood, electromagnetic compatibility, engineering application, bonding method, electromagnetic leakage.

INTRODUCTION

Recent rapid development of electronic devices such as TV, cellular phones, computers, etc., has given rise to electromagnetic interference (EMI) because almost all housings of these devices are made of materials (such as wood, cement, plastics, etc.) which are transparent to electromagnetic interference. EMI has become a new kind of environmental pollution which will influence the performance realization of other electrical devices (Tsai 2007), result in information compromising emanations (Kuhn 2005), and be harmful to human being and other organisms (Ozge 2003; Breckenkamp et al. 2003). Electromagnetic shielding is an adequate solution for the EMI problems.

A lot of electromagnetic shielding materials have been developed to act as a shield against electromagnetic radiation (Clayton 2006). Wood-based electromagnetic shielding composites gain lots of public interests due to their availability, cost, and renewability. Among the wood-based electromagnetic shielding composites (Chohachiro et al. 1999; Zhang and Liu 2004; Luo and Zhu 2004), electromagnetic shielding plywood have shown a lot of advantages and now have become the dominated product in developing wood-based electromagnetic shielding composites. Conductive shielding layers located inside the plywood prevent themselves from oxidation and corrosion and make them more durable. And the outside wood veneers make the composites more attractive appearance and use of the naturally-renewable environmental materials.

Luo and Zhu (2004) laminated the stainless and copper screens with wood veneers using the commercially available urea-formaldehyde (UF) and phenol-formaldehyde (PF) resins. The Electromagnetic shielding effectiveness of these composites was very good with the signal attenuation close to 40 dB. However, the mechanical performance of the composite made with UF resin failed to meet the performance standard and the use of slow curing PF resin could increase the manufacturing cost and low the productivity. Hua and Fu (1995) investigated the possibility of mixing three kinds of conductive powders (copper, carbon black, and graphite) into UF resin to make the EM shielding plywood. Although the area electrical resistance of the glue line was about 100 Ω, the overall EM shielding performance was not satisfied. Liu and Fu (2007) later used the copper fibers instead of the powder to mix with UF resin. The shielding effectiveness of the plywood reached 35 dB with the copper fiber filling ratio of 240 $g.m^{-2}$. However, Its low cost effectiveness made it difficult for the commercial application.

Compared to conductive powder form, metal fiber has higher aspect ratio which is critically related to its electrical conductivity. At the same concentration level, the higher the aspect ratio, the higher the conductivity, and the high shielding properties of composites (Toon 1990; Chen et al. 2004). That is one of main reasons that developing electromagnetic shielding plywood made by filling the conductive fibers into the UF resin directly has become the main research in this area in recent years. The good electromagnetic shielding performance is usually attributed to the high content of conductive fibers, but the negative effect of mixing the metal fiber with UF resin is that the more conductive metal fibers in resin will lower the bonding strength of the plywood. No research effort has been found to optimize the concentration of conductive fibers with acceptable bonding strength and the shielding effectiveness.

The engineering application of electromagnetic shielding materials is to bond all the materials together into a designing shield body. Bonding quality of the joint electromagnetic shielding materials is the most important factor which will affect the performance of the whole shield body. The seams between the joint electromagnetic shielding materials will result in electromagnetic leakage. The performance of shield body will be decreased with the increase of the length of seams (Xu 2008). Among the study of electromagnetic shielding plywood, all the research focused on developing the materials. No research effort has been found to study the engineering applications of materials.

The objective of this paper is first to develop indoor decorative plywood with high shielding performance and acceptable bonding strength. And then to look for a good bonding method for the engineering application of electromagnetic shielding plywood. Unlike the previous study to blend the conductive fibers into the resin directly, an innovative method is used to make a conductive sheet by uniformly blending the fibers with UF resin, sandwiching the resinated fibers with decorative papers on both sides, and hot-pressing it into sheet. The sheet will increase the contact area of the fiber and improve the electrical conductivity, and it will also improve the bonding surface with wood veneers. Brass fiber is selected as the conductive fiber mainly because of its superior electrical property, availability, and high aspect ratio (Chenga et al. 2000). The conductive sheets will be laminated with veneers to make novel electromagnetic shielding plywood. The structure of plywood is designed based on the multilayer electromagnetic shielding theory of Schelkunoff (1937). The shielding properties of plywood before and after bonding will be studied in this paper.

MATERIAL AND METHODS

Material

Urea formaldehyde resin (30-910) was provided by Taier, Beijing, China. The PH value of the UF resin was between 8.5 and 9.5, its solid content was 52 %, and the viscosity ranged from 110 to 170 cps (30°C). Chinese fir (*Larix*) veneers with the dimension of 700x700x2 mm were provided by Genghe Company (Neimengu, China) and were used to make the plywood samples. Copper foil was provided by Baote Company, Beijing, China. Its thickness was 0.03 mm.

A total of five concentration levels of brass fibers in the resin (12.5, 25, 50, 100, 200 g.m^{-2}) were used to make the conductive sheets. Fig. 1 showed the construction and fiber distribution on cross-section of the conductive sheet.

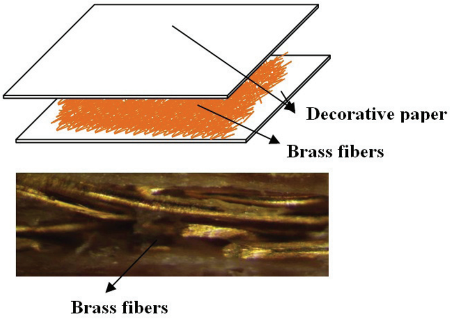

Fig. 1: Construction and fiber distribution on cross-section(40X) of conductive sheet (200 g.m^{-2}).

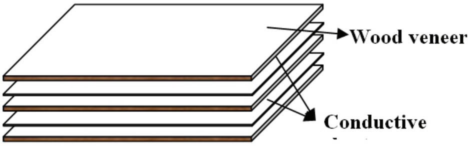

Fig. 2: Construction of EM Shielding plywood.

The conductive structure of the sheet was three dimension conductive network (Lu et al. 2009). Fig. 2 showed the construction of the plywood sample by laminating wood veneers with two layers of conductive sheets under hot-pressing for 6 minutes. The pressing temperature was 120°C and the press pressure was 1 MPa. The usage of UF resin was 150 g.m^{-2} for each bonding line. The plywood having the best shielding performance will be chosen for the study of engineering application.

Bonding technology

Opposite joint and overlap joint are the two ways in common use to connect the two conductors. For the engineering applications of common plywood, the two boards are usually connected by the glue. Through analyzing on the bonding method in the design of electromagnetic compatibility structure and considering the characteristics of electromagnetic shielding plywood (Conductive shielding layers located inside the plywood), the bonding interface was designed into opposite joint, inclined joint and step joint. The bonding interface was fixed by the glue, which was showed in Fig. 3.

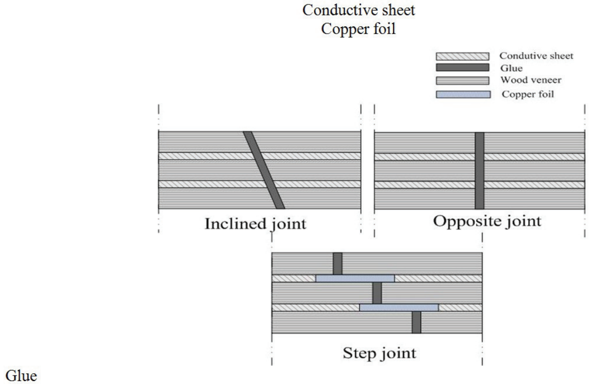

Fig. 3: Bonding methods of EM Shielding plywood.

Test methods

The electromagnetic shielding effectiveness (SE) is defined as the attenuation of an electromagnetic wave produced by its passage through a shield. It is expressed in decibels (dB) and calculated according to

$$SE= 10 \log (P_t / P_i)$$

where: P_t - the power of the transmitted wave,
P_i - the power of the incident wave.

The SE would be measured using two methods. The first was the coaxial cable method (also referred as transmission line method) according to the Chinese standard (SJ 20524, 1995). The setup consists of a vertical flanged test device with its input and output connected to a Hewlett-Packard (HP) 7401A EMC Analyzer (Fig. 4).

Standard annular specimens with the outer diameter of 115 mm and the inner diameter of 12 mm were cut from the plywood. The frequency of the transmitted signal ranged from 100 kHz to 1 GHz. The second method was the shielding room method according to the Chinese standard (GB 12190, 2006). The samples were installed onto the test hole located in the wall of shielding room (Fig. 5). The setup consists of transmitting and receiving antenna with their input and output connected to power amplifier (737LC-CE, KALMUS Company, USA) and spectrum analyzer (ROHDE & SCHWARA Company, USA). The frequency of the transmitted signal ranged from 30 MHz to 1 GHz. Standard square specimens with the dimension of 650x650 mm were cut from the plywood. Four EM shielding plywood samples were prepared for each run.

The shear strength along the bonding line was determined according to Chinese standard (GB 17657, 1999). Specimens were tested with the surface grain direction perpendicular to the length orientation of the specimen. The effective test area was 25 mm^2 in the center. The residual shear strength after being immersed in water for 3 hours at a temperature of 63±3°C was tested.

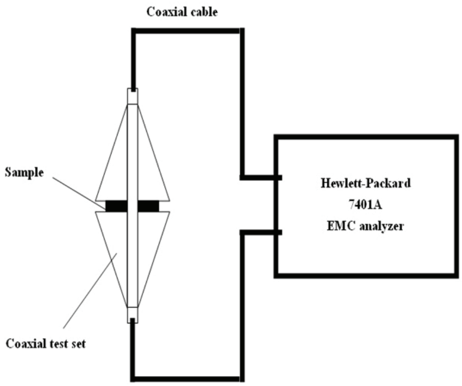

Fig. 4: Set-up for measuring the EM SE (coaxial test).

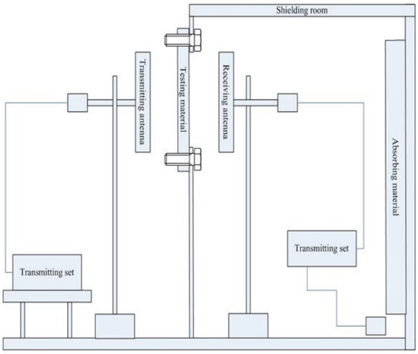

Fig. 5: Set-up for measuring the EM SE(shielding room test).

Eight panels were prepared for each run and four replicated specimens were cut from each panel.

RESULTS AND DISCUSSION

Shielding performance of plywood before bonding (Coaxial test)

The conductive sheets were used with wood veneers to make plywood samples and their SE were evaluated. Fig. 6 showed the SE of plywood samples made with two conductive sheets at different brass fiber concentrations (12.5 to 200 $g.m^{-2}$). It was noticed that the SE of the conductive sheets increased with the increasing concentration of brass fibers. It was also observed that the SE was decreased with the increase of the signal frequency. The reason was that there was a certain permeability within the sheet and the electrical reflection played an import role in the calculating the shielding effectiveness. When the frequency of the electrical signal increased, the reflection loss would be decreased and the SE would be decreased as well.

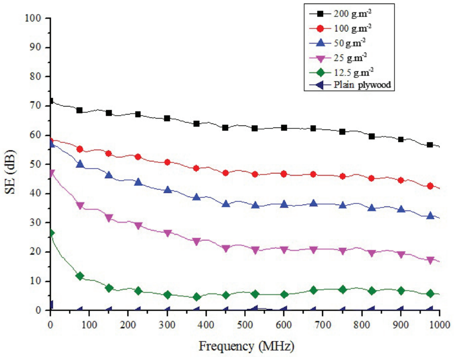

Fig. 6: Shielding effectiveness of plywood with two conductive sheets.

Plain plywood (without any conductive sheet) did not have any shielding effectiveness as shown in Fig. 6. For a product to be used commercially as effective shielding materials for electromagnetic radiation, its SE needs to be within the medium SE range which is between 30 and 60 dB (Du et al. 2000). From the results in this figure, it was also observed that the SE of plywood made with two conductive sheets (200 g.m^{-2} each) ranged from 55.87 to 71.75 dB (100 KHz to 1 GHz), which indicated it could be used as effective shielding materials for electromagnetic radiation. And this kind of plywood would also been chosen for the study of engineering application.

Shear strength of plywood

Shear strength were evaluated to examine bonding performance between the conductive sheets and the wood veneers. Tab. 1 presented the results of plywood shear strength at different brass fiber concentrations. The compatibility between the brass fiber and the adhesive would affect the bonding performance. Generally speaking, the more use of the brass fibers reduced the shear strength and caused the larger variations. However, all average values of the shear strength in the table exceeded the minimum value of 0.8 MPa which was required by the Chinese standard.

Tab. 1: Shear strength of plywood made with different brass fiber concentration.

Sample No.	**Brass fibers (g.m^{-2})**	**Shear strength**			**Wood failure**		
		Average	**Standard deviation**	**Coefficient of variation**	**Average**	**Standard deviation**	**Coefficient of variation**
		(MPa)		**(%)**			
1	12.5	1.63	0.46	28.2	84	30	35.7
2	25	1.35	0.22	16.3	100	0	0.0
3	50	1.36	0.25	18.4	65	40	61.5
4	100	1.33	0.26	19.5	80	38	47.5
5	200	1.17	0.23	19.7	76	35	46.1

Shielding performance of plywood after bonding (Coaxial test)

The SE of the composites was measured using the coaxial test and summarized in Tab. 2. Fig. 7 showed the SE comparison of plywood before and after bonding for a broad range of EM waves (100 KHz to 1 GHz). It was noticed that SE of plywood were decreased slightly after bonding in comparison to the plywood without seams. The observation that the SE of plywood resulted by the seams agreed with the behavior predicted by the EM compatibility theory.

Tab. 2: SE descent of plywood after bonding (Coaxial test).

Bonding method	**Step joint by copper foil**	**Opposite joint by glue**	**Inclined joint by glue**
Max descent of SE(dB)	9.45	8.04	6.47
Min descent of SE(dB)	3.91	0.92	3.29
Avg. descent of SE(dB)	6.81	5.71	5.10
Descent percent (%)	12.72	10.66	9.53

However, it also could be found that the difference of SE between three bonding methods were very small. It was difficult from the Tab. 2 and Fig. 7 to identify which method was the best.

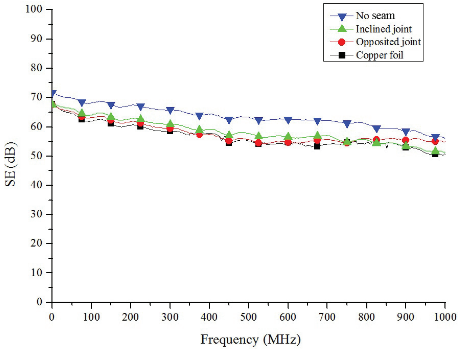

Fig. 7: Comparative SE of plywood after bonding (Coaxial test).

The reason was that the joint seams were located on the diameter direction of samples. According to the inner electric field distribution of flange coaxial test device (Fig. 8), it could be seen that the direction of the electric field radiated from the center of the annular specimen.

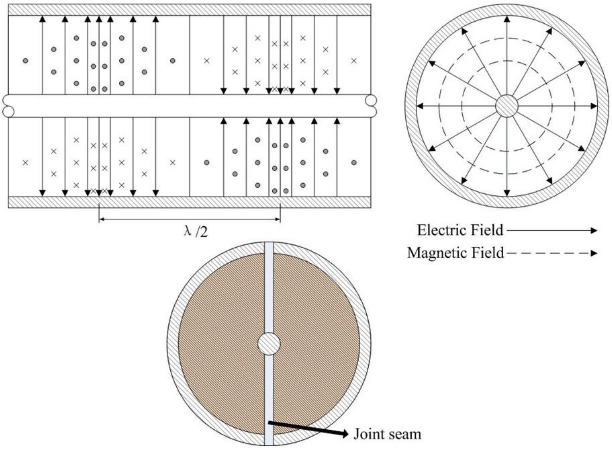

Fig. 8: Distribution of inner field of device of flange and the location of joint seam.

The direction of joint seam was same as that of the electric field. There was no potential difference between the upper and lower edge of seam. The existence of seam had no significant effects on the shielding performance. In spite of different bonding methods, there was no much difference on the effects. So it was concluded that the coaxial test could not be effectively evaluated the bonding quality when the joint seam was located in the diameter direction of the annular specimen.

Shielding performance of plywood after bonding (shielding room test)

For the shielding room test method, the polarization direction of the electrical filed was perpendicular to the seam which was shown in Fig. 9. The seam was regarded as a secondary emission antenna because of the potential difference between the upper and lower edge of seam (Wu and Zou 2004). According to theory of electromagnetic field, it meant that the electromagnetic wave would pass through the seam which resulted in great decline of shielding performance.

Tab. 3 showed the SE descent of plywood after bonding under three different methods using window test method. Fig. 10 showed the SE comparison of plywood before and after bonding for a broad range of EM waves (30 MHz to 1 GHz). Contrast analysis clearly indicated that the SE descent of plywood using copper foil connection method decreased smaller than that of the other two connecting methods. The reflection type shields of the electromagnetic leakiness request to shield body had good electricity continuity. It was mainly attributed to the low impedance path between two separated conductive sheets which avoiding large electromagnetic leakage. For the copper foil connection method, the copper foil had good electrical contact with the brass fibers which were uniformly distributed in the conductive sheets through laminated press process. The copper foil was used as a good conductive lap to connect the two boards. At the same time, the seam between the two layer of copper foils also led to a small SE decline because the surface of wood veneer was not smooth. It was concluded that the step joint connected by copper foil was the best bonding method to suppress electromagnetic leakage.

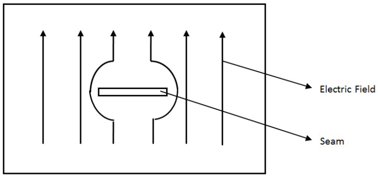

Fig. 9: The polarization direction of the electrical field of Shielding room test.

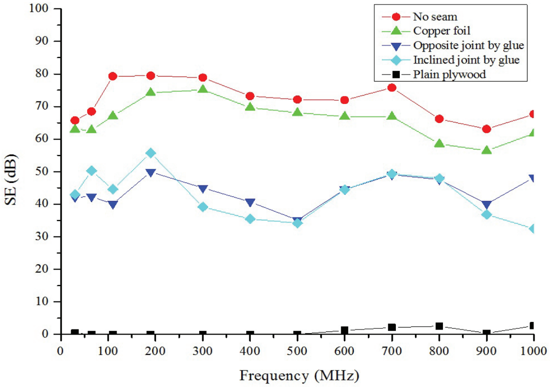

Fig. 10: Comparative SE of plywood after bonding (Shielding room test) .

Tab. 3: SE descent of plywood after bonding (Shielding room test).

Bonding method	**Step joint by copper foil**	**Opposite joint by glue**	**Inclined joint by glue**
Maximal descent of SE (dB)	12.20	39.17	39.74
Minimum descent of SE (dB)	2.70	18.62	18.18
Average descent of SE (dB)	5.29	28.10	29.04
Descent percent of SE average (%)	7.37	39.13	40.44

It was also observed that there was no big differences between the methods of opposite joint and inclined joint. For the two methods, the separated conductive sheets were connected by a layer of non-conducting base of glue. The glue did not form effective conductive pathways to connect the conductive sheets between two boards, which thereby causing the big electromagnetic leakage. The length of the seam was the same, so the decreased degree of SE was at the same level.

CONCLUSIONS

The plywood used for electromagnetic shielding were constructed by laminating the two layers of conductive sheets with wood veneers. The SE of plywood ranged from 55.87 to 71.75 dB (100 KHz to 1 GHz). It was indicated it could be used as effective shielding materials for electromagnetic radiation. The shielding properties of plywood after bonding were evaluated using two test methods. The results showed that the seams between the joint plywood resulted in the decline of electromagnetic performance. From the coaxial test, it was found that this test method could not be effectively evaluated the bonding quality when the joint seam was located in the diameter direction of the annular specimen. From the shielding room test, the SE descent of plywood using copper foil connection method decreased smaller than that of the other two connecting methods, which indicated that the copper foil connection was the best bonding method to suppress the electromagnetic leakage.

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