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Cone calorimeter evaluation of reinforced hybrid wood–aluminum composites

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Abstract

Combustion performance for three types of wood–aluminum composites was investigated using cone calorimetry tests. The results revealed that time to ignition of the specimens was increased and more than 100 times after the lamination of 1.6-mm-thick aluminum alloy sheet on the surface (from 17 to 1990 s). And residual mass of the wood–aluminum composites was improved and almost quadrupled (from 21.795% to 81.664%). The peak heat release rate, average heat release rate, total heat release, and mean mass loss rate of wood–aluminum composites with 1.6-mm-thick aluminum alloy sheet on the surface were decreased to 70.18%, 48.71%, 24.27%, and 80.60%, respectively. However, yields of both CO and CO_2 are slightly improved with the increase in the thickness of aluminum alloy sheet because of incomplete combustion. The application of aluminum alloy sheets to the wood-based composites is an effective method for improving the combustion performance.

Keywords

Wood–aluminum composites, cone calorimeter tests, combustion performance, aluminum alloy sheet

Introduction

Wood–metal composites (WMC) have been widely used in load-bearing structures such as I-joists, studs, large roof spans, and compartment floors due to their high strength and

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dimensional stability. Research has been conducted to investigate mechanical properties,[1,2] electromagnetic shielding,[3] combustion performance,[4,5] and fire performance.[6] Aluminum alloy has gained high levels of public interest because of its excellent properties of recyclability, formability, light weight, and high strength. The wood–aluminum composites (WAC) combined the best properties of wooden material and metal and would be the dominated product in the future application. Experiment has been conducted to characterize mechanical,[7] electromagnetic shielding,[8] and fire performance[9] of the WAC. However, little information was available to characterize the combustion characteristics of the WAC.

Wood-based composites have been contributing to fire hazards resulting in numerous injuries and fatalities due to their inherent combustion performance.[10,11] Improving of combustion performance for the wood-based composites plays a more and more important role in its future applications due to the obliged provision of flame-retardant rating for the materials in the public places according to GB20286.[12] Yang[13] studied the combustion performance of aluminum/wood decorative composite with 0.27-mm-thick aluminum alloy foil on the surface. Results of the cone calorimeter analysis indicated that the peak heat release rate (PHRR) and total HRR were significantly decreased and the decrement was as much as 97.3% and 96.6%, respectively. Additionally, the 1.57-mm-thick aluminum skins were cladded to the fire side or the interior of the balsa wood core/phenolic composite skin sandwich panels to prepare fire restrictive composite. And cone calorimeter testing with an incident heat flux of 100 kW/m^2 and room corner fire testing were conducted in accordance with ASTM E1354 and ISO 9075, respectively. The experiment results revealed that additional built-in engineering fire protection was observed after the lamination of aluminum skins on the surface.[14] Little research effort has been found which studied the combustion performance of the wood-based composites laminated with aluminum alloy sheet. Thus, it is necessary to further study the combustion characteristics of the WAC, which will help promote its engineering application.

The aluminum alloy sheets (in different position and different thickness) were laminated to the oriented strand board (OSB) to prepare WAC. Their combustion characteristics would be analyzed by the cone calorimeter in accordance with ISO 5660-1 (*Cone calorimeter method*). Several important performance parameters during the cone calorimeter such as time to ignition (TTI), HRR, total heat release (THR), mass loss rate (MLR), residual mass, smoke produce rate (SPR), total smoke production (TSP), and CO and CO_2 yield have been analyzed to characterize combustion performance of the WAC. The main combustion residue observation was also conducted to further analyze the flame-retardant mechanism of WAC. The purpose of this study was to provide insights to better understand the combustion characteristics of several types of WAC.

Experimental

Materials

The 3003 Aluminum alloy sheets were obtained from the Jinglutengda Metal Material Co., Ltd, Beijing, China. And the aluminum alloy composition is presented in Table 1. The size of alloy sheet was 1220 × 2440 mm^2 (length × width). And the thickness was 0.2, 0.4, 0.8, and 1.6 mm, respectively. The melting point of 3003 aluminum alloy sheet is 650°C. In this study, the aluminum alloy sheets were abrasively cleaned by sanding to remove weak boundary layers of oxide and scale so as to enhance the mechanical interlocking between aluminum

Table 1. Chemical compositions of 3003 aluminum alloy sheet.

Type	Si	Fe	Cu	Mn	Zn	Al
Weight content (%)	0.60	0.70	0.05–0.20	1.0–1.5	0.10	96.90–97.55

Table 2. Description of specimens tested in the cone calorimeter.

Specimen no.	Specimen code[a]	Thickness of A (mm)	Location of A
0	O + O + O	0	Without A
0.2–1	O + A + O + A + O	0.2	In the middle
0.2–2	A + O + O + O + A	0.2	On the surface
0.4–3	O + A + O + A + O	0.4	In the middle
0.4–4	A + O + O + O + A	0.4	On the surface
0.8–5	O + A + O + A + O	0.8	In the middle
0.8–6	A + O + O + O + A	0.8	On the surface
1.6–7	O + A + O + A + O	1.6	In the middle
1.6–8	A + O + O + O + A	1.6	On the surface

O: OSB; A: aluminum alloy sheet.
[a]Specimen code indicates type of the composites.

alloy sheet and adhesive.[15,16] The diphenyl-methane-diisocyanate (MDI) resin was provided by Huntsman Polyurethanes Shanghai Ltd, Shanghai, China. The color of MDI resin was dark brown and the viscosity at 25°C was 180 cps. It would be used for hot-pressing in this experiment. The OSB with the dimension of $1220 \times 2440 \times 6.5$ mm^3 (length × width × thickness) provided by Detongyuan Building Materials Trade Co., Ltd, Beijing, China, was used to manufacture WAC.

Preparation of the WAC

Three types of WAC were prepared in this study, shown in Table 2 and Figure 1(a) to (c). Additionally, the thickness of aluminum alloy sheets applied to this study was 0.2, 0.4, 0.8, and 1.6 mm, respectively. The WAC were hot-pressed at a pressure of 1.5 MPa for 20 min. The hot-pressing temperature was 150°C. The usage of MDI resin was 100 g/m^2 for each bonding line.

Cone calorimeter analysis

The cone calorimeter based on the oxygen combustion principle has been widely used to analyze the combustion properties of materials, providing a variety of quantifiable heat release parameters. The heat release characteristics of WAC were investigated by the cone calorimeter in accordance with ISO 5660-1. And Cone calorimeter analysis of the WAC is shown in Figure 2(a).[17] In this study, the specimens were exposed to the fire with a surface heat flow density of 50 kW/m^2.[18] The specimens to be measured have a size of 100×100 mm^2 (length × width). The combustion performance data such as TTI, HRR, THR, MLR, SPR, TSP,

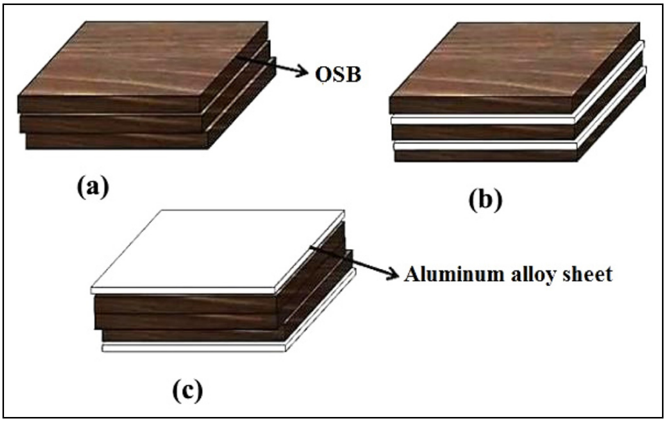

Figure 1. Physical structure of the wood–aluminum composites: (a) control panels without aluminum alloy sheets, (b) composite with aluminum alloy sheets placed in the middle, and (c) composite with aluminum alloy sheets placed on the surface.

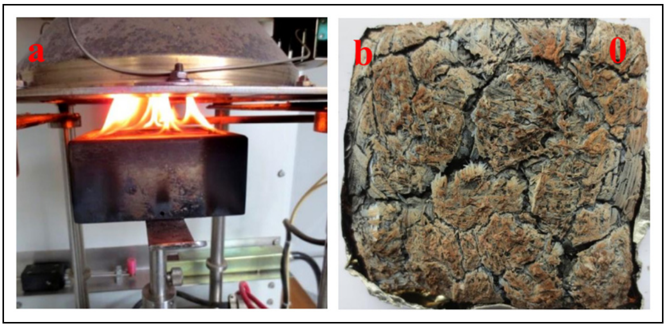

Figure 2. (a) Cone calorimeter analysis of the wood–aluminum composites and (b) combustion residue observation of the composite without aluminum alloy sheet.

CO, and CO_2 yield were obtained and analyzed. The specimens tested in the cone calorimeter are listed in Table 1.

Results and discussion

Combustion residue observation of the WAC

The main combustion residue observation of combustion test specimens was obtained as illustrated in Figures 2(b) and 3. It was observed that the black residue of WAC with aluminum alloy sheet on the surface left was carbonized OSB during the fire test, indicating the incomplete combustion of WAC (Figure 3). The completed combusted OSB of the control specimens and the first layer of WAC with aluminum alloy sheet in the middle was gray or brown (Figures 2(a) and 3(a)).

Figure 3. Combustion residue observations of the wood–aluminum composites with aluminum alloy sheets (a) in the middle or (b) on the surface.

The control composite without aluminum alloy sheet was observed to complete combustion during the cone calorimeter analysis. For the composites with aluminum alloy sheet in the middle, the first layer of OSB was combusted sharply once exposed to fire (Figure 3(a)). And then the interior aluminum alloy sheet became a surface aluminum alloy sheet and prevented the second layer of OSB combusting (Figure 3(a)). For the composites with aluminum alloy sheet on the surface, the 0.2- and 0.4-mm aluminum alloy sheets were too thin to resist the pressure of the volatile gases from the OSB, and the aluminum alloy sheets did not remain intact (Figure 3(b): 0.2–1 and 0.4–4). Increasing the thickness of the aluminum alloy sheet from 0.4 to 0.8 mm increased the heat release of the WAC. And the 1.6-mm-thick aluminum alloy sheet was thick enough to remain intact (Figure 3(b): 1.6–8).

HRR of the WAC

Figure 4 presents the HRR curves of the composites with or without the lamination of aluminum alloy sheet as a function of time. The PHRR and average HRR of the WAC was

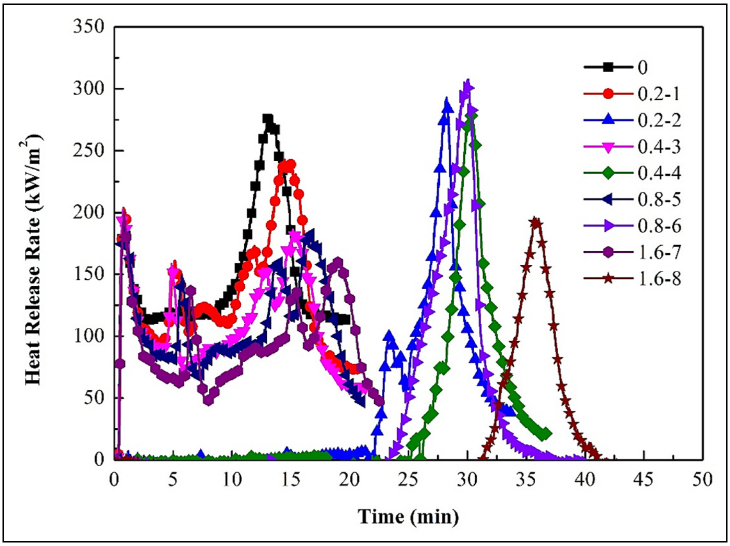

Figure 4. Heat release rate of the wood–aluminum composites.

Table 3. Peak heat release and average heat release rate of the wood–aluminum composites.

Specimen no.	Peak HRR (kW/m^2)	Time to peak HRR (s)	Average HRR (kW/m^2)
0	278.11 (100.00%)	804 (100.00%)	146.68 (100.00%)
0.2–1	242.79 (87.30%)	868 (107.96)	132.84 (90.56%)
0.2–2	292.88 (105.13%)	1694 (210.70%)	104.61 (71.32%)
0.4–3	213.44 (76.75%)	51 (6.3433%)	101.43 (69.15%)
0.4–4	285.50 (102.66%)	1813 (225.50%)	74.92 (51.08%)
0.8–5	191.54 (68.87%)	50 (6.2189%)	107.94 (73.95%)
0.8–6	307.51 (110.57%)	1803 (224.25%)	73.17 (49.89%)
1.6–7	200.94 (72.25%)	49 (6.09%)	93.26 (63.58%)
1.6–8	195.17 (70.18%)	2148 (267.16%)	71.45 (48.71%)

HRR: heat release rate.

illustrated in Table 3. For the composites with aluminum alloy sheet in the middle, the WAC exhibited three-stage combustion. The third PHRR of WAC was greater than that of the first for the WAC laminated with 0.2-mm-thick aluminum alloy sheet. However, the first PHRR value was greater than the values for the second one when the thickness of aluminum alloy sheet increases from 0.4 to 1.6 mm. Furthermore, the time to PHRR also exhibited the same conclusion. For the composites with aluminum alloy sheet on the surface, only one PHRR was observed during the cone calorimeter analysis.

It was found that PHRR of the composites was decreased with the increase in thickness of the aluminum alloy sheet ranging from 0.2 to 1.6 mm. And the specimens with aluminum alloy sheet on the surface exhibited greater peak HRR than that of the control specimens and specimens with aluminum alloy sheet in the middle until the thickness of aluminum alloy sheet increases to 1.6 mm. For example, the sample with the 0.2-mm-thickness aluminum alloy sheet on the surface shows 292.88 kW/m^2, and it was reduced down to 195.71 kW/m^2 (decrease by 34.98%) when the thickness of aluminum alloy sheet reached 1.6 mm. Additionally, the same results was found in the WAC with aluminum alloy sheet laminated in the middle. Therefore, it is evident that increasing the thickness of aluminum alloy sheet contributed to noticeably reducing the HRR and flammability of the WAC.

It was also found that the average HRR of WAC decreased with the increasing thickness of aluminum alloy sheet. And the average HRR observed for the WAC with 1.6-mm-thick aluminum alloy sheet on the surface was reduced by more than 50% (from 146.68 to 71.45 kW/m^2). And the average HRR of WAC with aluminum alloy sheet in the middle was also decreased from 132.84 to 93.26 kW/m^2 as the thickness of aluminum alloy sheet increases from 0.2 to 1.6 mm. The OSB was protected by the aluminum alloy sheet on the surface. The 1.6-mm-thick aluminum alloy sheet was thick enough to remain intact, but the 0.2- and 0.4-mm-thick aluminum alloy sheets did not. The melting of thin aluminum alloy sheet resulted in further combustion of the OSB and increase in HRR.

Comprised with the composites without aluminum alloy sheet, time to peak HRR of the WAC with 0.2-mm-thick aluminum alloy sheet in the middle only increased slightly (from 804 to 868 s). And HRR of the WAC reaches to the peak value at the first peak HRR with the further increases of the aluminum alloy sheet thickness and exhibits similar time to peak HRR (the corresponding time to peak HRR was 51, 50, and 49 s, respectively). This may be due to the combustion of the first layer of OSB and release a great deal of heat once exposed to fire during the cone calorimetry tests. For the WAC with aluminum alloy sheet on the surface, time to peak HRR was significantly increased and more than twice (from 804 to 2148 s). This may be due to the protection of aluminum alloy sheet on the surface. Increasing the thickness of the aluminum alloy sheet from 0.2 to 1.6 mm significantly delayed the time to peak HRR of the WAC.

TTI

The TTI is shown in Figure 5. As observed from the results in Figure 5, TTI difference between the control composites and the composites with aluminum alloy sheets in the middle was small. And the TTI of specimens was significantly increased with the lamination of aluminum alloy sheets on the surface. The TTI was increased by more than 100-fold (from 17 to 1990 s) after the lamination of 1.6-mm-thick aluminum alloy sheet on the surface. For the control specimens and WAC with aluminum alloy sheet in the middle, the first layer of specimens was OSB and was combusted once exposed to fire. For the composites with aluminum alloy sheet on the surface, the OSB was prevented combusting by aluminum alloy sheet located on the surface. As the thickness of aluminum alloy increases from 0.2 to 1.6 mm, the greater the thickness of the aluminum alloy sheet, the greater the TTI delay. In another study, Moysey and Muir[19] worked with shiny galvanized steel or aluminum on wood and estimated that the time for ignition of wood was four times longer with these materials on the surface.

THR of the WAC

The THR and fire hazard level of the WAC are shown in Table 4. And Figure 6 shows THR of the WAC after combustion. It was indicated that lamination of the aluminum alloy sheet

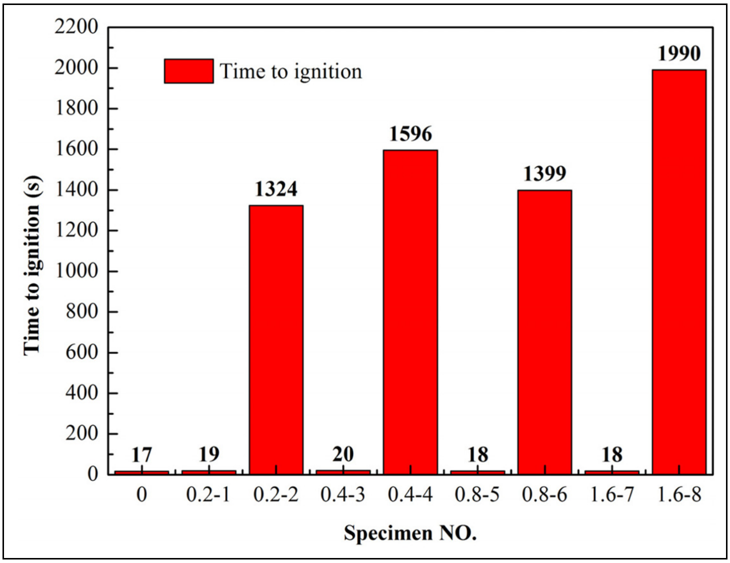

Figure 5. Time to ignition of the wood–aluminum composites.

Table 4. THR and fire hazard level of the wood–aluminum composites.

Specimen no.	THR (MJ/m^2)	Fire hazard level[3]
0	172.79 (100.00%)	High fire hazard
0.2–1	162.33 (93.95%)	High fire hazard
0.2–2	86.24 (49.91%)	Intermediate fire hazard
0.4–3	129.63 (75.06%)	High fire hazard
0.4–4	63.50 (36.75%)	Intermediate fire hazard
0.8–5	135.47 (78.40%)	High fire hazard
0.8–6	74.92 (43.36%)	Intermediate fire hazard
1.6–7	126.46 (73.19%)	High fire hazard
1.6–8	41.93 (24.27%)	Intermediate fire hazard

THR: total heat release.
[3]Arbitrary scales suggested for THR[20] are: very low fire hazard: 0.1–1, low fire hazard: 1.0–10, intermediate fire hazard: 10–100, and high fire hazard: 100–1000.

noticeably declined the THR of WAC. THR observed for the WAC was reduced by more than 70% when the 1.6-mm-thick aluminum alloy sheet was located on the surface (from 172.79 to 41.93 MJ/m^2). It was found that the THR of the composites with aluminum alloy sheets in the middle and the control composites were more than 100 with high fire hazard level of combustion. And that of the composites with aluminum alloy sheet on the surface reached to the scale of intermediate fire hazard level. The reason was that the OSB was prevented combusting by the aluminum alloy sheet located on the surface during the cone calorimeter analysis. And the 1.6-mm-thick aluminum alloy sheet was thick enough to remain intact and prevented the OSB combustion, but the 0.2- and 0.4-mm-thick aluminum

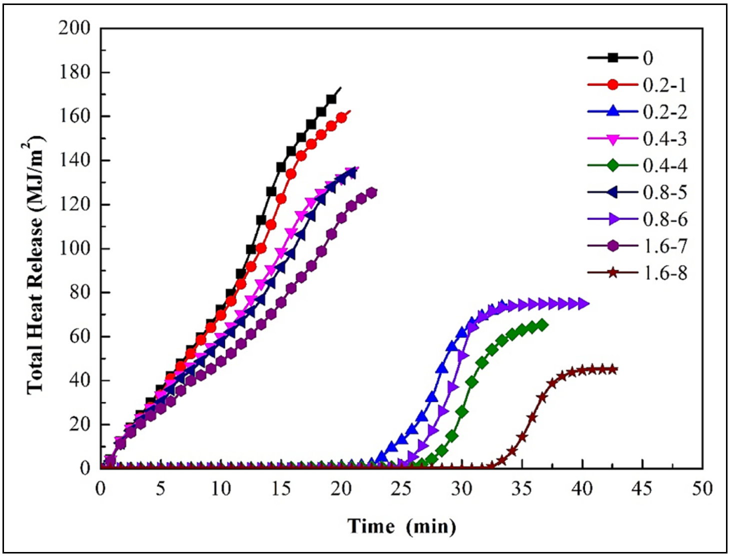

Figure 6. Total heat release of the wood–aluminum composites.

Table 5. MLR and residual mass of the wood–aluminum composites.

Specimen no.	Peak MLR (g/s)	Average MLR (g/s)	Residual mass (%)
0	0.6550 (100.00%)	0.0799 (100.00%)	21.795 (100.00%)
0.2–1	0.5086 (77.65%)	0.0826 (103.38%)	23.538 (108.00%)
0.2–2	0.5481 (83.68%)	0.0776 (97.12%)	58.044 (266.32%)
0.4–3	0.4992 (76.21%)	0.0713 (89.24%)	33.489 (153.65%)
0.4–4	0.4934 (75.34%)	0.0740 (92.62%)	66.903 (306.96%)
0.8–5	0.4642 (70.87%)	0.0766 (95.87%)	42.759 (196.19%)
0.8–6	0.6540 (99.85%)	0.0619 (77.47%)	61.828 (283.68%)
1.6–7	0.4400 (67.17%)	0.0689 (86.23%)	55.594 (255.07%)
1.6–8	0.4746 (72.46%)	0.0644 (80.60%)	81.664 (374.69%)

MLR: mass loss rate.

alloy sheets did not. Therefore, increasing the thickness of the aluminum alloy sheet from 0.2 to 1.6 mm increased the combustion performance of the WAC and resulted in the decline of THR.

MLR and residual mass of the WAC

MLR and residual mass of the WAC are shown in Table 5. The WAC exhibited lower peak and average MLR than the composites without aluminum alloy sheet. Additionally, the peak and average MLR were decreased with the increase in thickness of the aluminum alloy sheet (Table 5). For the composites with aluminum alloy sheet in the middle, it was observed that the first layer of OSB combusted sharply once exposed to fire and result in the increasing of

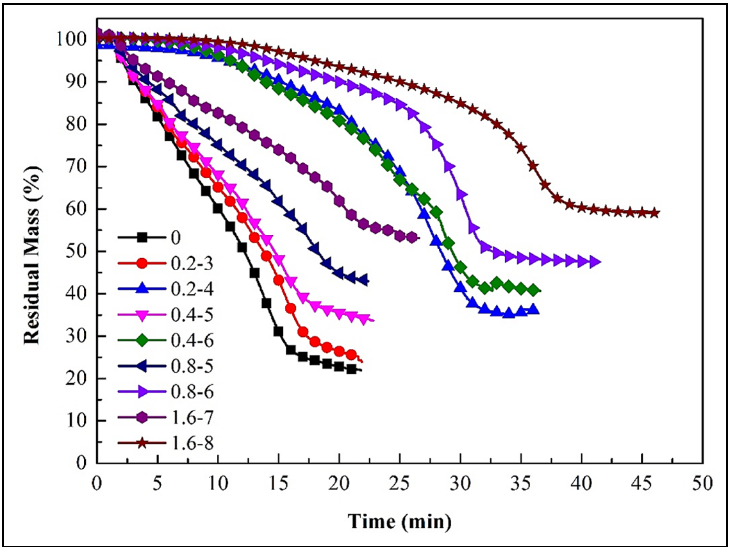

Figure 7. Residual mass of the wood–aluminum composites after combustion.

MLR. And then the interior aluminum alloy sheet became a surface aluminum alloy sheet and prevented the OSB combusting. For the composite with aluminum alloy on the surface, the aluminum alloy sheet on the surface did not change and prevented the OSB burning, resulting in the decreasing of MLR.

Figure 7 shows the residual mass of the WAC. As illustrated in Table 5 and Figure 7, increasing the thickness of aluminum alloy sheet from 0.2 to 1.6 mm remarkably increased the residual mass of the WAC. For the WAC with aluminum alloy sheet in the middle, the residual mass of WAC was increased to 255.07% as the thickness of aluminum alloy sheet increases from 0.2 to 1.6 mm. And that of the WAC with 1.6-mm-thick aluminum alloy sheet on the surface was 374.69%. The reason was that lamination of the aluminum alloy sheet prevents the OSB combusting during the test and resulted in the increasing of residual mass.

SPR and TSP

Figures 8 and 9 show the SPR and TSP of the WAC after combustion, respectively. As illustrated in Figures 8 and 9, SPR and TSP of the composites were significantly decreased after the lamination of aluminum alloy sheets on the surface or in the middle. The time to peak SPR for WAC with aluminum alloy sheet on the surface was obviously delayed with the increasing thickness of aluminum alloy sheet, and the values of peak SPR were also decreased. This can be explained by the lamination of the aluminum alloy sheet on the surface which prevents combusting of OSB and smoke releasing from tested specimens, especially the aluminum alloy sheet was thick enough to remain intact (Figure 3(b): 1.6–8). Additionally, TSP was shown in Table 6. The TSP observed for the composites was reduced by more than 90% after the lamination of aluminum alloy sheets on the surface or in the middle. And the difference of TSP between WAC with aluminum alloy sheets on the surface and in the middle was not significant (Table 6).

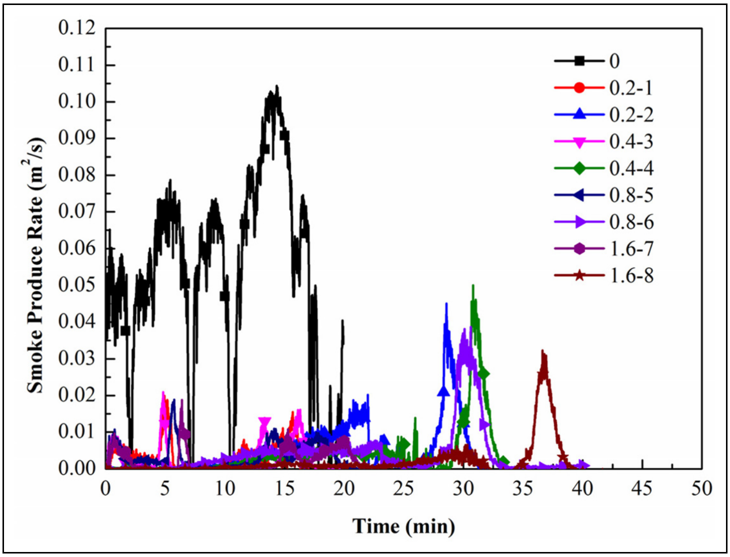

Figure 8. Smoke produce rate of the wood–aluminum composites.

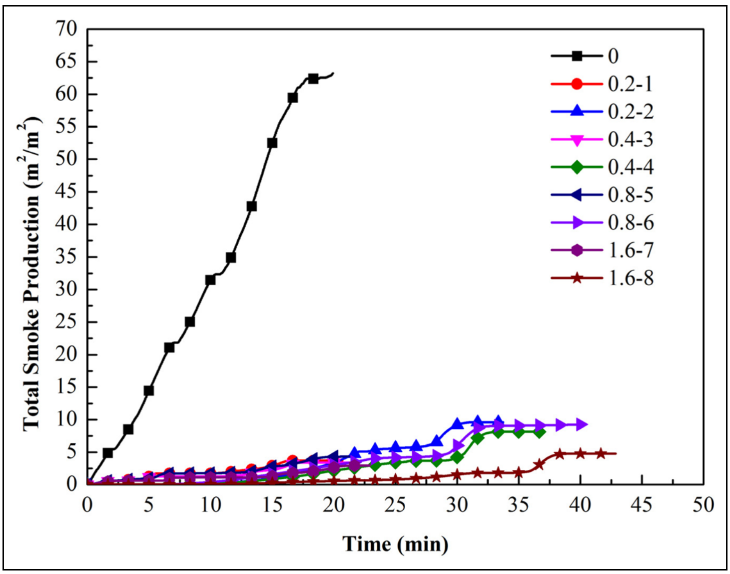

Figure 9. Total smoke production of the wood–aluminum composites.

CO and CO_2 yield of the WAC

Figure 10 exhibits the CO and CO_2 yield of the WAC. It was found that the CO yield of WAC was much higher than that of the composites without aluminum alloy sheet (from

Table 6. TSP of the wood-aluminum composites.

Specimen no.	0	0.2–1	0.2–2	0.4–3	0.4–4	0.8–5	0.8–6	1.6–7	1.6–8
TSP (m^2/m^2)	62.42 (100.00%)	3.67 (5.88%)	4.99 (7.99%)	3.37 (5.40%)	4.47 (7.16%)	4.28 (6.86%)	5.21 (8.35%)	2.90 (4.65%)	2.97 (4.75%)

TSP: total smoke production.

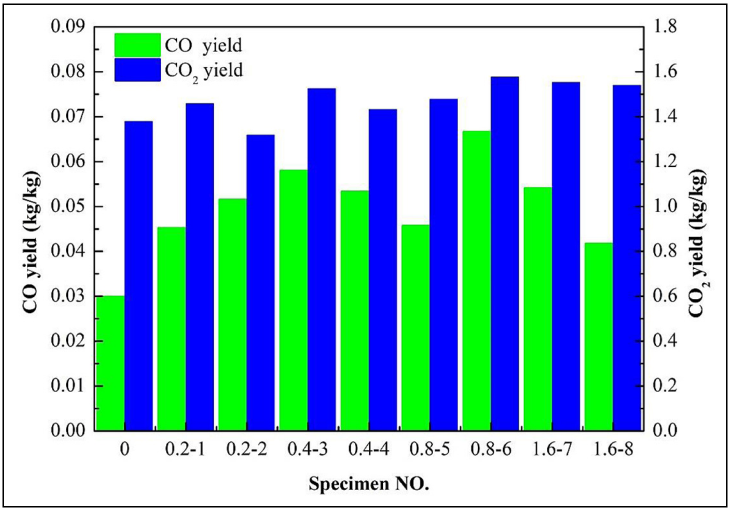

Figure 10. CO and CO_2 yield of the wood–aluminum composites.

0.0299 to 0.0541 kg/kg). This is mainly attributed to the suppression effect of the aluminum alloy sheet on the OSB, leading to the incomplete combustion of the OSB and increasing the generation of CO during the combustion process. For the WAC with aluminum alloy sheets on the surface, the CO yield increases when the thickness of aluminum alloy sheet increases from 0.2 to 0.8 and then decreases as the thickness of aluminum alloy sheet increases to 1.6 mm. And for the WAC with aluminum alloy sheets in the middle, the CO yield increases when the thickness of aluminum alloy sheet increases from 0.2 to 0.4 and then decreases as the thickness of aluminum alloy sheet increases to 0.8 mm. The reason was that the 1.6-mm-thick aluminum alloy sheet was thick enough to remain intact during cone test, but the 0.2- and 0.4-mm-thick aluminum alloy sheets did not. Comprised with the composites without aluminum alloy sheet, CO_2 yield of the WAC was slightly increased and about 10% (from 1.3787 to 1.5527 kg/kg). For the WAC with aluminum alloy sheet on the surface, the CO_2 yield increases when the thickness of aluminum alloy sheets increases from 0.2 to 0.8 and then decreases with the further increase in the thickness of aluminum alloy sheets. For the WAC with the 0.2-mm-thick aluminum alloy sheet, the relatively thin aluminum alloy sheet on the surface cannot effectively prevent the OSB combusting and thus the OSB burns once exposed to the fire and a great deal of CO_2 generates. The greater thickness of aluminum alloy sheet on the surface leads to the incomplete combustion of the OSB, thereby decreasing the production amount of CO_2. For instance, CO_2 yield of the WAC with aluminum alloy sheet in the middle, the first layer of OSB burns sharply once exposed to fire during the cone test and results in the generation of CO_2.

Conclusion

The objective of this study was to evaluate the combustion characteristics of the WAC laminated with aluminum alloy sheet (in different positions and different thicknesses). The combustion characteristics of the WAC were measured in terms of TTI, HRR, THR, MLR, and residual mass to characterize the combustion performance of WAC. Results revealed that the WAC with aluminum alloy sheet on the surface exhibited more excellent combustion performance than that of the WAC with aluminum alloy sheet in the middle. The TTI of the specimens with aluminum alloy sheet laminated on the surface is remarkably prolonged from 17 to 1900 s when the thickness of aluminum alloy sheet increases to 1.6 mm. The PHRR, average HRR, THR, and mean MLR of WAC with 1.6-mm-thick aluminum alloy sheet on the surface were decreased to 70.18%, 48.71%, 24.27%, and 80.60%, respectively. Residual mass of the WAC was noticeably improved and almost quadrupled after the lamination of 1.6-mm-thick aluminum alloy sheet on the surface. However, the greater thickness of aluminum alloy sheet leads to the higher yields of CO and CO_2 due to the incomplete combustion. The TSP observed for WAC was reduced more than 90% after the lamination of aluminum alloy sheets on the surface or in the middle, and effects of thickness and position of aluminum alloy sheet on TSP of WAC were not significant. It was also indicated that lamination of aluminum alloy sheet on the surface decreased the fire hazard of WAC efficiently as described in THR analysis. It was concluded that the presence and position of the aluminum alloy sheet remarkably affected the combustion performance of WAC.

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Declaration of conflicting interests

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References

1. Song XB and Lam F. Stability analysis of metal-plate-connected wood truss assemblies. *J Struct Eng* 2012; 138: 1110–1119.
2. Gallo E, Schartel B, Acierno D, et al. Tailoring the flame retardant and mechanical performance of natural fiber-reinforced biopolymer by multi-component laminate. *Compos Part B* 2013; 44: 112–119.
3. Wang LJ, Sun LL and Li J. Electroless copper plating on *Fraxinus mandshurica* veneer using glyoxylic acid as reducing agent. *BioResources* 2010; 6(3): 3493–3504.

4. Hashim R, How LS, Kumar RN, et al. Some of the properties of flame retardant medium density fiberboard made from rubber wood and recycled containers containing aluminum trihydroxide. *Bioresource Technol* 2005; 96: 1826–1831.
5. Schnal S, Planinc I and Turk G. Fire analysis of timber composite beams with interlayer slip. *Fire Saf J* 2009; 44: 770–778.
6. Moss PJ, Buchana AH, Fragiacomo M, et al. Fire performance of bolted connections in laminated veneer lumber. *Fire Mater* 2009; 33: 223–243.
7. Fogle EJ, Lattimer BY, Feih S, et al. Compression load failure of aluminum plates due to fire. *Eng Struct* 2012; 34: 155–162.
8. Lu KY, Fu F, Cai ZY, et al. Nondestructive methods of evaluating mechanical properties of wood electromagnetic shielding composites. In: *Proceeding of 16th international symposium on nondestructive testing and evaluating of wood*, Beijing, P.R. China, 12–14 October 2009, pp. 208–215.
9. Lu KY, White RH, Fu F, et al. Reinforced hybrid wood-aluminum composites with excellent fire performance. *Holzforschung* 2015; 69(8): 1027–1037.
10. Wei P, Hu LH, Yang RX, et al. Full scale test on fire spread and control of wooden buildings. *Procedia Eng* 2011; 11: 355–359.
11. Lowden LA and Hull TR. Combustion performance behaviour of wood and a review of the methods for its reduction. *Fire Sci Rev* 2013; 2: 1–19.
12. GB 20286-2006: Requirements and mark on burning behavior of fire retarding products and subassemblies in public place. Chinese National Standardization Management Committee. Beijing, P.R. China. 2006.
13. Yang HQ. Preparation and properties of aluminum/wood decorative composite (PhD Dissertation). Chin Acad For, Beijing, P.R. China, 2012; 56–68.
14. Morgan AB and Toubia E. Cone calorimeter and room corner fire testing of balsa wood core/phenolic composite skin sandwich panels. *J Fire Sci* 2014; 32(4): 328–349.
15. Arrowsmith DJ and Clifford AW. A new pretreatment for the adhesive bonding of aluminum. *Int J Adhes Adhes* 1985; 5: 40–42.
16. Zhang JS, Zhao XH, Zuo Y, et al. The bonding strength and corrosion resistance of aluminum alloy by anodizing treatment in a phosphoric acid modified boric acid/sulfuric acid bath. *Surf Coat Tech* 2008; 202: 3149–3156.
17. Yu YM, Hou JF, Dong ZQ, et al. Evaluating the flammability performance of Portland cement-bonded particleboards with different cement-wood ratios using a cone calorimeter. *J Fire Sci* 2016; 34(3): 199–211.
18. Li B, Qian SP, Zhao JM, et al. Fire resistance of *Miscanthus floridulus* straw stalk boards treated by diammonium hydrogen phosphate. *China Wood Ind* 2012; 26(4): 49–52.
19. Moysey EB and Muir WE. Pilot ignition of building materials by radiation. *Fire Technol* 1968; 4(1): 46–50.
20. Xu Q, Jin C, Zachar M, et al. Test flammability of PVC wall panel with cone calorimeter. *Procedia Eng* 2013; 62: 754–759.

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