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Research on the preparation and properties of foamed PP/wood flour composites

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Abstract

In order to improve the toughness of the wood-polymer composites, the microcellular structure was introduced to the polypropylene (PP) based wood-polymer composites by the technology of continuous extrusion in this article. In order to improve the mechanical and thermal properties of the samples further, the content of both wood flour (WF) and the chemical blowing agent were investigated. Besides, the compound foaming agents were also applied in the process of extrusion. According to the experimental results, the addition of WF contributed to increase both the softening temperatures and the apparent densities of the samples, and the best mechanical properties and microcellular structure were obtained when the mass ratio of WF to PP increased to 3/7. In addition, compared with the granular blowing agent, the powdered foaming agent showed a great advantage in dispersion, which helped to improve the bubble morphology and the mechanical strengths of the samples. Furthermore, the minimum bubble size and the maximum bubble density were both achieved at the powder content of 1 phr.

1. Introduction

During the past decades, a great development has been made on the molding technology of wood-polymer composites, which makes the products prepared by the wood-polymer composites become more popular in many fields, such as construction, industry and agriculture [1, 2]. The wood-polymer composites have gradually replaced the applications of the timbers in many fields because of the environmental advantages, the high chemical resistance and the good processing characteristics. But the disadvantages of the composites, such as high density and poor toughness, make the timbers still necessary in construction and other fields. But the application of the timbers with poor degradation resistance and low durability often result in great expenditures on repair and replacement. Besides, the shortage of timbers in the world also promotes the appearance of the lightweight and ductile products prepared by wood-polymer composites. Polypropylene (PP) is one of the most productive polymers, and the PP based wood-polymer composites is also one of the most widely used composites in the world today.

The previous studies indicated that the lightweight composites could be prepared by the foaming technology. But the bubbles’ size of conventional foamed composites was large and non-uniform, which showed no assist in improving the toughness of the composites. In recent years, the microcellular structure was found helpful to improve the toughness of the composites. The bubbles with the size less than 100 μm can effectively passivate the crack tips and increase the energy used for crack growth during the process of fracture [2–6]. Besides, the microcellular structure also provides the composites with the excellent heat insulation and sound insulation.

However, the wood-polymer composites based on the amorphous polymers, such as polyvinyl chloride (PVC) and polystyrene (PS), are easily to achieve the microcellular structure by the microcellular foaming technology [1, 7–10]. The preparation of the microcellular wood-polymer composites based on the crystalline polymers, such as PP, is more difficult. On one hand, the melt strength of PP decreases quickly as the progress
temperature exceeds the melt temperature, which is unable to constrain the excessive expansion of the bubbles. On the other hand, the degradation temperature of wood flour (WF) is very close to the processing temperature of PP, which also increases the difficulty of the preparation [11]. Moreover, the microcellular structure of the composites are also affected by the content and size of both the foaming agent [10, 12–14] and the nucleating agent [4, 15], and the compatibility between WF and resin matrix [16]. In addition, most of the researches about the microcellular composites focus on the batch foaming technology [17, 18] and the injection foaming technology [15, 19]. The microcellular extrusion foaming technology of the composites is seldom investigated.

The previous work indicated that blending with polyolefin elastomer (POE) could effectively improve the melt viscosity of the composites [20], and the interfacial adhesion between PP and WF was significantly improved with the addition of maleic anhydride grafted polypropylene (MAH-g-PP) [21]. Besides, the nucleating agent of talc with the size of 23 μm could effectively improve the microcellular structure of the samples at the content of 10 phr. In addition, the previous rheological tests also indicated that the complex viscosity of the composites was much higher than that of pure resin. In this article, the effects of WF content on both the flowability and the properties of the composites were investigated. Moreover, the compound foaming agents, including the organic and the inorganic foaming agents, were also applied to the formulation of the composites, and the content of the foaming agents was also investigated to optimize the bubble morphology and the mechanical properties of the composites.

2. Experimental

2.1. Raw materials

The wood–polymer composites are mainly composed of the resin matrix and WF, and the resin matrix is the polymer blends of PP and POE. PP (B1002W), purchased from Sinopec Beijing Yanshan Petrochemical Company (China), has a melt flow index of 1.0 g/10 min at 230 °C/2.16 kg and a density of 0.9 g/cm³. POE (DF605), purchased from Mitsui Chemicals (Japan), has a density of 0.86 g cm⁻³ and a melt flow index of 0.5 g/10 min at 190 °C/2.16 kg. WF, purchased from HC wooden Co. (China), has the size of 150 μm. Besides, the fillers, such as talc and MAH-g-PP, are also added in the composites. The talc powder, purchased from Haicheng Talc Powder Manufacturer (China), has the powder size of 23 μm. MAH-g-PP (CA100), purchased from Arkema Co., Ltd (France), has the melt flow index of 10 g/10 min at 190 °C/0.325 kg. In addition, there are two types of foaming agents used in the extrusion process, including azodicarbonamide (AC) and sodium bicarbonate (NaHCO₃). The AC powder is purchased from Selon Industrial Co. (China), and the foaming masterbatch of NaHCO₃ (EF405) is purchased from Eiwa chemical Ind. Co., Ltd (Japan).

2.2. Preparation of PP/WF composites

In order to improve the melt strength of PP, the particles of PP and POE were first blended by a high-speed mixer at the ratio of 6/4, and then melt blended by a twin-screw extruder with the diameter of 20 mm and the L/D of 40 (Kunshan Kesun Rubber and Plastic Machinery Co., China). Next, the pellets prepared by the twin-screw extruder were blended with WF, talc, MAH-g-PP and other fillers by the mixer and the twin-screw extruder. Besides, the WF should be dried in an oven at 80 °C for 24 h before mixing. In addition, the formulations of the PP/WF composites prepared in this article and the process parameters of the twin-screw extruder are listed in tables 1 and 2 respectively.

2.3. Extrusion foaming of composites

The pellets of PP/WF composites prepared in the above steps were extruded into the flake-shaped samples with the width of 80 mm and the height of 8 mm by a single-screw extruder foaming system [20].

Besides, before extrusion, the pellets were mixed with the foaming agent in the high-speed mixer for 3 min. Besides, the liquid paraffin was also added to make the pellets wrapped by the AC powder. Considering the decomposition temperature of the foaming agent and the melt temperature of the composites, the process parameters of the single-screw extruder foaming system, such as zone temperature and screw speed, are listed in figure 1. At last, the flake-shaped samples were cut into the test pieces with different shapes.

2.4. Characterizations

2.4.1. Melt flow rate (MFI)

The melt flow rate of the composites was tested by a melt indexer (RL-Z1B1, Shanghai S R D Scientific Instrument Co., Ltd, China). Besides, each sample was repeatedly tested at 230 °C/5 kg 5 times and averaged. The melt flow rate of the composites was tested according to ASTM D1238 and calculated as follows:
where MFI is the melt flow rate of the composites (g/10 min), m is the weight of splines (g), and t is the cutting time interval (s).

2.4.2. Mechanical properties
The impact strength of the samples was tested according to GB/T 1843 by an impact testing instrument (KBANM-II, Chengde Taiding Testing Machine Manufacturing Co., Ltd, China). Before testing, a side-edge notch with the depth of 2 mm was machined on each sample. In addition, the tensile strength and the flexural strength of the samples were all tested by a universal testing machine with the maximum load of 5 KN (KXWW, Chengde Taiding Testing Machine Manufacturing Co., Ltd, China). The tensile strength was tested according to GB/T 1040.2 with the draw speed of 10 mm min\(^{-1}\), and the flexural strength was tested according to GB/T 9341 with the cross-head speed of 10 \(\times\) mm min\(^{-1}\). Besides, each sample was repeatedly tested 5 times and averaged.

2.4.3. Morphological properties
The fracture surfaces of the samples were observed by a scanning electron microscope (SEM) (S-4700, Japan Hitachi Company, Japan) after tensile tests, and the fracture surfaces were coated with a thin gold layer before...
observation. Besides, the SEM photographs were analyzed by a software (Image Pro Plus 6.0) to calculate the bubble size and density of the samples.

The bubble size $\bar{d}$ is the average diameter of all bubbles counted in the photographs, which is calculated as follows:

$$\bar{d} = \frac{\sum_{i=1}^{n} d_i}{n}$$

where $d_i$ is the diameter of a single bubble, and $n$ is the number of bubbles counted in the SEM photographs. Besides, the bubble density $N_0$ is the number of bubbles per unit volume of the composites, which is calculated as follows:

$$N_0 = \left[ \frac{nM^2}{A} \right]^{3/2} \frac{\rho_0}{\rho_f}$$

where $A$ is the area of the SEM photograph ($\text{cm}^2$), $n$ is the number of bubbles counted in the photograph, $M$ is the magnification of the photograph, $\rho_0$ is the density of the unfoamed sample and $\rho_f$ is the density of the foamed sample.

2.4.4. Vicat softening temperature

The Vicat softening temperature of the samples was tested by a HDT-VST meter (KXRW-300CL-3, Chengde Taiding Testing Machine Manufacturing Co., Ltd, China). The Vicat softening temperature of the samples was tested according to ASTM D1525 with the heating rate of 120 °C/h and the load of 1 kg. Besides, each sample was repeatedly tested 3 times and averaged.

2.4.5. Thermogravimetric analysis (TGA)

The thermogravimetric analysis was conducted by an analyzer (TGAQ50, Waters Corporation, United States). The samples were tested in nitrogen atmosphere with a heating rate of 10 °C/min ranging from 40 to 400 °C, according to ASTM E2402.

2.4.6. Apparent density

The apparent density of the samples was tested by a densitometer (AR-300VP, Dongguan HongTuo Instruments Co., Ltd, China) with the accuracy of 0.0001 g cm$^{-3}$. Besides, the samples were tested according to ASTM D792, and over 5 samples were tested for each data point.

3. Results and discussions

3.1. Effect of WF content on the properties of the samples

3.1.1. Melt flow rate

The melt flowability of the composites was characterized by MFI in this article. As shown in figure 2, the addition of WF resulted in the decline of MFI of the composites, which indicated the increase of the melt viscosity. With the increase of the WF content, the MFI of the composites gradually decreased from 0.4 to 0.33 g/10 min. On one hand, the added MAH-g-PP could not only form ester bonds with WF, but also form physical interlocks with PP molecular chains, which resulted in the decreased flowability of the composites $[21–24]$. On the other hand, the excessive addition of WF could also result in the internal friction between WF particles.

3.1.2. Bubble morphology

The SEM photographs and the bubble diameter distributions of the samples with different mass ratio of PP to WF are shown in figure 3, and the bubble size and density of the samples analyzed by the software are listed in figure 4. According to these figures and the previous work, the added WF contributed to decrease the bubble size and increase the bubble density at low content. On one hand, the addition of WF contributed to increase the melt viscosity of the composites, which provided a higher bubble growth resistance. On the other hand, the added WF also played the role of bubble nucleation points, which helped to increase the bubble density. But, when the WF content was very high, the particles of WF were much easier to contact with each other, which could result in the escape of gas used for bubble growth from the gaps between particles. Besides, the high content of WF also made it easier for the WF particles to contact with the surface of screw and barrel, which would accelerate the degradation of WF particles because of the shear effect and damage the microcellular structure of the samples. As a result, the minimum bubble size of 71 μm and the maximum bubble density of $2.7 \times 10^4 \text{cells/cm}^3$ were both obtained at the ratio of 3/7.
3.1.3. Mechanical properties
The mechanical strengths of the samples with different WF content were tested and the results were listed in figure 5. According to the data in figure 5(a), the impact strength of the samples decreased with the content of WF. As the mass ratio of WF to PP increased from 1/9 to 5/5, the impact strength of the samples decreased from 8.0 to 3.9 kJ m\(^{-2}\), which decreased by 51.3%. The data in figure 5(a) indicated that the increased WF content made it easier for the particles of WF to contact with each other, and the load was difficult to transfer between the particles of WF, which reduced the toughness of the samples.

Moreover, according to the data in figure 5(b), with the increase of the WF content, the tensile strength of the samples increased first and then decreased. At first, the tensile strength increased by 19.4% as the mass ratio increased from 1/9 to 3/7, which could be attributed to the improved microcellular structure and the increased effective forced area of the samples [21]. But as the mass ratio exceeded 3/7, both the destruction of the microcellular structure and the degradation of WF particles led the tensile strength to decrease from 8.2 MPa to 4.1 MPa. As a result, the maximum tensile strength was achieved at the mass ratio of 3/7.

Similar with the tensile strength, the flexural strength of samples also increased first and then decreased as the ratio exceeded 3/7, which was shown in figure 5(c). At first, the flexural strength increased by 21.4% as the mass ratio increased from 1/9 to 3/7, which was also attributed to the improved microcellular structure and the increased effective forced area of the samples [21]. But, compared with the samples prepared with the mass ratio of 3/7, the flexural strength of the samples prepared with the ratio of 4/6 decreased to 20.5 MPa, which decreased by 7.2%, which could be attributed to the destruction of the microcellular structure and the degradation of WF particles. Besides, as the ratio increased to 5/5, the degradation of WF particles caused by the shear effect of the screw in the extrusion process made it difficult to prepare the bending splines that met the test requirements.

3.1.4. Vicat softening temperature
The heat resistance of the composites was characterized by the Vicat softening temperature in this article. As shown in figure 6, the softening temperature increased from 128.4 to 147.4 °C with the addition of WF. The improved heat resistance could be attributed to the fact that WF dispersed in the resin matrix could hinder the thermal movement of molecular chains, and the higher content of WF resulted in the greater hindrance. As a result, the softening temperature increased by 14.8% as the mass ratio of WF to PP increased from 1/9 to 5/5.

3.1.5. Apparent density
The densities of the samples were shown in figure 7. According to the data in figure 7, the addition of WF could increase the density of the samples. As the mass ratio of WF to PP increased from 1/9 to 5/5, the density of the
samples increased by 29.1%. The previous work indicated that the increased content of WF showed less effect on the density of the un-foamed samples prepared by the technology of extrusion. As a result, the changed density could be mainly attributed to the microcellular structure. On one hand, the low content of WF resulted in the excessive expansion of bubbles, which led to the decrease of the density. On the other hand, the excessive addition of WF resulted in the escape of gas generated by the foaming agent, which led to the increase of the density.

Figure 3. Bubble morphologies and bubble diameter distribution of the foaming samples with different WF content: (a) mass ratio of WF to PP 1/9, (b) mass ratio of WF to PP 2/8, (c) mass ratio of WF to PP 3/7, (d) mass ratio of WF to PP 4/6, (e) mass ratio of WF to PP 5/5.
Figure 3. (Continued.)

Figure 4. Bubble size and bubble density of the foaming samples with different WF content.
Figure 5. Mechanical properties of the samples with different ratio of PP to WF: (a) notched impact strength, (b) tensile strength, (c) flexural strength.

Figure 6. Vicat softening temperature of the samples with different WF content.
3.2. Effect of compound foaming agents on the properties of the samples

3.2.1. Thermogravimetric Analysis (TGA)

In this article, two types of foaming agents were mixed in different proportions to investigate the effect of compound foaming agents on the properties of the samples, and the thermogravimetric curves of the two types of foaming agents are shown in figure 8. According to the curves in figure 8, the foaming masterbatch of EF405 decomposed in two steps, while the AC powder decomposed in one step. With the increase of the temperature, EF405 would decompose from 175 to 183 °C first and then decompose from 191 to 213 °C, which caused the release of steam and carbon dioxide. Compared with EF405, the AC powder decomposed with the release of nitrogen, carbon dioxide and ammonia in the temperature interval from 170 to 183 °C, mainly at the temperature of 180 °C.
3.2.2. Bubble Morphology
The SEM photographs and the bubble diameter distributions of the samples added with the compound foaming agents in different proportions are shown in figure 9, and the bubble size and density of the samples analyzed by the software are listed in figure 10. The compound foaming agents used in this article are composed of the granular inorganic foaming agent EF405 and the powdered organic foaming agent AC. According to the data in figures 9 and 10, the increased proportion of AC in the compound foaming agents contributed to decrease the bubble size and increase the bubble density. Compared with the granular EF405 foaming agent, the powder of AC foaming agent could be uniformly coated on the surface of the pellets of PP/WF composites under the action of liquid paraffin in the high-speed mixer, which made the gas caused by the degradation of foaming agent achieve the uniform dispersion easily. Besides, the shorter degradation temperature interval of AC foaming agent made the degradation position easier to predict and the foaming process more controllable, which was conducive to achieve the microcellular structure. As a result, the bubble size and density of the samples were 162 μm and 1.9 × 10^4 cells/cm³ respectively, when the compound foaming agents only contained EF405. By comparison, the addition of AC powder made the bubble size decreased by 55.6% and the bubble density increased by 40.7%.

3.2.3. Mechanical properties
The mechanical strengths of the samples prepared with the compound foaming agents were tested and the results were listed in figure 11. According to the data in figure 11(a), the impact strength of the samples mainly increased with the proportion of AC foaming agent in the compound foaming agents. Compared with EF405 foaming agent, the addition of AC foaming agent could increase the impact strength of the samples by 4.2%. Besides, according to the data in figures 11(b) and (c), the tensile strength and flexural strength of samples also increased with the proportion of AC in the compound foaming agents. Compared with EF405, the addition of AC could increase the tensile strength and the flexural strength by 15.9% and 32.7% respectively. According to the bubble diameter distributions of the samples shown in figure 9, the increased proportion of AC foaming agent in the compound foaming agents could effectively reduce the maximum bubble size and decrease the number of large bubbles, which contributed to increase the effective forced area and the maximum load of the samples [21].

3.3. Effect of AC content on the properties of the samples
3.3.1. Bubble morphology
The SEM photographs and the bubble diameter distributions of the samples with different content of AC are shown in figure 12, and the bubble size and density of the samples analyzed by the software are listed in figure 13. According to the data in figure 13, with the increase of the content of AC foaming agent, the bubble size decreased first and then increased, while the bubble density increased first and then decreased. The minimum bubble size and the maximum bubble density were both obtained at the AC content of 1 phr. At first, the increased content of the AC powder provided the higher amount of gas used for the nucleation and the growth of bubbles, which helped to increase the driving force and overcome the interfacial energy of the bubble nucleation. On one hand, part of the generated gas dissolved in the melt first and the excess gas flowed into the newly formed bubble cores to support bubble growth under the constraint of the melt. On the other hand, when the gas concentration was much higher than the solubility of the melt contributed to the formation of bubble cores [5, 6, 8]. As a result, the increased AC content contributed to improve the microcellular structure of the samples. But as the content exceeded 1 phr, the excessive gas made the bubbles expand and coalesce into bigger ones, which caused great damage to the microcellular structure of the samples.

3.3.2. Mechanical properties
The mechanical properties of the samples with different AC content were tested, and the results are listed in figure 14. According to the data listed in figure 14(a), with the increase of AC content, the impact strength of the samples increased first and then decreased, and the maximum impact strength was obtained at the AC content of 1 phr. Besides, according to the data in figures 14(b) and (c), the tensile strength and the flexural strength of samples also mainly increased with the AC content and then decreased as the AC content exceeded 1 phr. Generally speaking, the samples achieved the best mechanical properties at the AC content of 1 phr, which was greatly affected by the microstructure of the samples. By comparison, the maximum bubble density and minimum bubble size were obtained at the AC content of 1 phr, which could effectively increase the energy used for crack growth and the valid forced area.
Figure 9. Bubble morphologies and bubble diameter distribution of the foaming samples with various compound foaming agent: (a) mass ratio of EF405 to AC 3/0, (b) mass ratio of EF405 to AC 2/1, (c) mass ratio of EF405 to AC 1/2, (d) mass ratio of EF405 to AC 0/3.
Figure 10. Bubble size and bubble density of the foaming samples with various compound foaming agents.

Figure 11. Mechanical properties of the samples with different mass ratio of EF405 to AC: (a) notched impact strength, (b) tensile strength, (c) flexural strength.
4. Conclusions

In order to improve the microcellular structure of the samples, the effects of WF content, compound foaming agents and AC content were investigated, and some conclusions were summarized and listed as follows:

1. The addition of WF could increase the melt viscosity of the composites and the Vicat softening temperature of the samples. Besides, both the largest mechanical strengths and the best microcellular structure of the samples were obtained when the mass ratio of WF to PP was 3/7. In addition, the addition of WF also resulted in the increase of the apparent density.

Figure 12. Bubble morphologies and bubble diameter distribution of the foaming samples with different AC content: (a) 0.25 phr, (b) 0.5 phr, (c) 1.0 phr, (d) 1.5 phr, (e) 2.0 phr.
Figure 12. (Continued.)

Figure 13. Bubble size and bubble density of the foaming samples with different AC content.
Compared with AC foaming agent, the foaming agent of EF405 decomposed in two steps within a longer temperature interval. Besides, the increased proportion of EF405 in the compound foaming agents caused great damage to the microcellular structure of the samples. In addition, compared with EF405 foaming agent, the mechanical strengths of the samples with the addition of AC foaming agent, such as impact strength, tensile strength and flexural strength, were increased by 4.2%, 15.9% and 32.7% respectively.

As the content of the AC foaming agent increased, both the bubble density and the mechanical strengths of the samples increased first and then decreased, while the bubble size decreased first and then increased. As a result, both the largest mechanical strengths and the best microcellular structure of the samples were obtained with the AC content of 1 phr.

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**References**

[1] Faruk O and Matuana L M 2008 Nanoclay reinforced HDPE as a matrix for wood-plastic composites *Compos. Sci. Technol.* 68 2073–7

[2] Zhang S, Rodrigue D and Riedl B 2010 Preparation and morphology of polypropylene/wood flour composite foams via extrusion *Polym. Composite* 26 731–8
[3] Guo G, Rizvi G M, Park C B and Lin W S 2004 Critical processing temperature in the manufacture of fincelled plastic/wood-fiber composite foams J. Appl. Polym. Sci. 91 621–9
[4] Colton J S and Suh N P 1987 Nucleation of microcellular foam: theory and practice Polym. Eng. Sci. 27 500–3
[5] Martini J, Waldman F and Suh N 1982 The production and analysis of microcellular thermoplastic foams Annual Technical Conference-Society of Plastics Engineers 28 674–6
[6] Lee J G and Flumerfelt R W 1984 Microcellular closed cell foams and their method of manufacture J. Colloid Interf. Sci. 184 335–48
[7] Matuana I M, Park C B and Balatinicz J J 1997 Processing and cell morphology relationships for microcellular foamed PVC/wood-fiber composites Polym. Eng. Sci. 37 1137–47
[8] Petchwattana N and Covavisaruch S 2011 Influences of particle sizes and contents of chemical blowing agents on foaming wood plastic composites prepared from poly(vinyl chloride) and rice hull Mater. Design 32 2844–50
[9] Li Q and Matuana I M 2003 Foam extrusion of high density polyethylene/wood-flour composites using chemical foaming agents J. Appl. Polym. Sci. 88 3139–50
[10] Gwon J G, Lee S Y, Kang H and Kim J H 2012 Effects of sizes and contents of exothermic foaming agent on physical properties of injection foamed wood fiber/HDPE composites Int. J. Precis. Eng. Man. 13 1003–7
[11] Araújo J R, Waldman W R and Paoli M A D 2008 Thermal properties of high density polyethylene composites with natural fibres: coupling agent effect Polym. Degrad. Stab. 93 1770–5
[12] Sun Y, Ueda Y, Suganaga H, Haruki M, Kihara S I and Takishima S 2015 Experimental and simulation study of the physical foaming process using high-pressure CO2 J. Supercrit. Fluid 107 733–45
[13] Sun Y, Ueda Y, Suganaga H, Haruki M, Kihara S I and Takishima S 2015 Pressure drop threshold in the foaming of low-density polyethylene, polystyrene, and polypropylene using CO2 and N2 as foaming agents J. Supercrit. Fluid 103 38–47
[14] Hoffmann C, Lang M, Heidemeyer P, Bastian M, Fischer K and Sonntag M 2016 Foam extrusion of pp-based wood plastic composites with chemical blowing agents and the celuka technique J. Cell. Plast. 53 623–38
[15] Zhou Y, Gong W and He L 2017 Application of a novel organic nucleating agent: cucurbit[6]uril to improve polypropylene injection foaming behavior and their physical properties J. Appl. Polym. Sci. 134 44538
[16] Zhang Z X, Chen D L, Kwak K H, Xin Z X and Kuk Kim J 2013 Effects of compatibilizers on the physico-mechanical and foaming properties of polypropylene/wood-fiber composites J. Vinyl. Addit. Techn. 19 250–7
[17] Jiang X L, Liu T, Xu Z M, Zhao L, Hu G H and Yuan W K 2009 Effects of crystal structure on the foaming of isotactic polypropylene using supercritical carbon dioxide as a foaming agent J. Supercrit. Fluid. 48 167–75
[18] Zhang Z X, Zhang J, Lu B X, Xin Z X, Kang C K and Kim J K 2012 Effect of flame retardants on mechanical properties, flammability and foamability of PP/wood–fiber composites Compos. Part B-Eng. 43 150–8
[19] Ameli A, Jahani D, Nofar M, Jung P U and Park C B 2014 Development of high void fraction poly lactide composite foams using injection molding: mechanical and thermal insulation properties Compos. Sci. Technol. 90 88–95
[20] Wang S, Xue P, Jia M and Chen K 2019 Effect of polymer blends on the properties of foamed wood-polymer composites Mater. Today 12 1971
[21] Wang S, Xue P, Jia M and Chen K 2019 Extrusion foaming behavior of wood plastic composites based on PP/POE blends Mater. Res. Express 6 115345
[22] Feng C, Li Z, Wang Z, Wang B and Wang Z 2017 Optimizing torque rheometry parameters for assessing the rheological characteristics and extrusion processability of wood plastic composites J. Thermoplast. Compos. 2017 1–18
[23] Mansour S H, Asaad J N, Iskander B A and Tawfik S Y 2008 Influence of some additives on the performance of wood flour/polyolefin composites J. Appl. Polym. Sci. 109 2243–9
[24] Li B, Jiang H, Guo L and Shi H 2008 Comparative study on the effect of manchurian ash and larch wood flour on mechanical property, morphology, and rheology of HDPE/wood flour composites J. Appl. Polym. Sci. 107 2520–30