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Dependence of Mechanical and Thermal Properties of Thermoplastic Composites on Electron Beam Irradiation

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Abstract Since the restrictions for environmental protection being strengthened, thermoplastics reinforced with natural fibers (NF's), such as jute, kenaf, flax, etc. have appeared as alternatives to chemical plastics for automobile interior materials. In this study, the thermal conductivity, tensile strength, and deformation of several kinds of thermoplastic composites composed of 50% polypropylene (PP) and 50% natural fiber (NF) irradiated by an electron beam (energy: 0.5 MeV, dose: 0–20 kGy) were measured. The length and thickness of PP and NF are 80 ± 10 mm and 40–120 μm, respectively. The results show that the thermal conductivity and the tensile strength changed and became minimum, when the dose of the electron beam was 10 kGy. However, the effect of the dose on the deformation was not clear.

Keywords Deformation · Electron beam irradiation · Tensile strength · Thermal conductivity · Thermoplastic composite

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1 Introduction

Natural fibers as substitutes for glass fibers in composite components have gained renewed interest in the automotive industry. Carmakers are looking increasingly at thermoplastics reinforced with natural fibers to reduce weight and cost in interior and engine components. Of all the thermoplastic matrices available, polypropylene (PP) shows the most potential benefits when combined with natural fibers in making composites for industrial applications [1].

A notable shortcoming in the natural fiber–thermoplastic system is the poor bonding between the natural fiber and the plastic. This is due to the dissimilar chemical nature, i.e., the natural fiber surface is hydrophilic, while plastics are generally hydrophobic. In order to develop composites with better mechanical properties, it is necessary to impart hydropobicity to natural fibers by suitable treatments [2]. The selection of proper coupling agents and the use of electron beam irradiation are important to improve fiber-matrix adhesion so as to produce composite materials with superior strength [3,4]. Also, the energy saving in connection with car air-conditioning becomes very important, therefore, the thermal and mechanical properties of thermoplastic composites were investigated in our previous study [5]. In this study, the thermal conductivity, tensile strength, and deformation of thermoplastic polypropylene (PP) boards reinforced with natural fiber (NF) and coupling agents, such as maleated polypropylene (MAPP) [6] and silane [7] are measured before and after irradiation with an electron beam.

2 Material Preparation

A twin screw co-rotating extruder (SCE) was developed for combining of 48.5 mass% PP, 48.5 mass% natural fibers, and 3.0 mass% MAPP (maleated polypropylene). MAPP acts as a compatiblizing agent in polymer blends and is particularly effective when one polymer is hydrophilic and the other polymer is hydrophilic. The shortened 50–80 mm lengths of natural fibers, e.g., kenaf/hemp/flax/sisal and micron-size PP and MAPP powder were used for composite fabrication. The main motivations for using natural fiber to replace glass fiber are the low cost (∼1/3 of glass fibers), low density (∼1/2 of glass), acceptable specific strength properties, and enhanced energy recovery, CO_2 sequesterization, and biodegradability.

Parts of the mats were soaked in a 0.3% silane aqueous solution. The individual silane (aminoethylamino-propyltrimethoxy silane or AEAPTMS) coupling agent molecules are expected to attach to natural fibers and form a continuous link. Three groups of mats (Group A: PP (50%) + NF (50%), Group B: PP (48.5%) + NF (48.5%) + MAPP (3%), Group C: Group B soaked in 0.3% silane aqueous solution) were prepared.

All groups of the mats were irradiated by the electron beam at a speed of $30\,\mathrm{mm\cdot s^{-1}}$ with doses of 0, 5, 10, 15, and 20 kGy. The energy of the electron is 0.5 MeV. The processed mats were subjected to compression molding; the materials were kept under contact temperature at 200°C for about 15 min under mild pressure followed by pressing at 2.4–2.5 MPa pressure for about 2 min followed by cooling under pressure to obtain the final composite plaques for testing. We assumed that nearly all of the

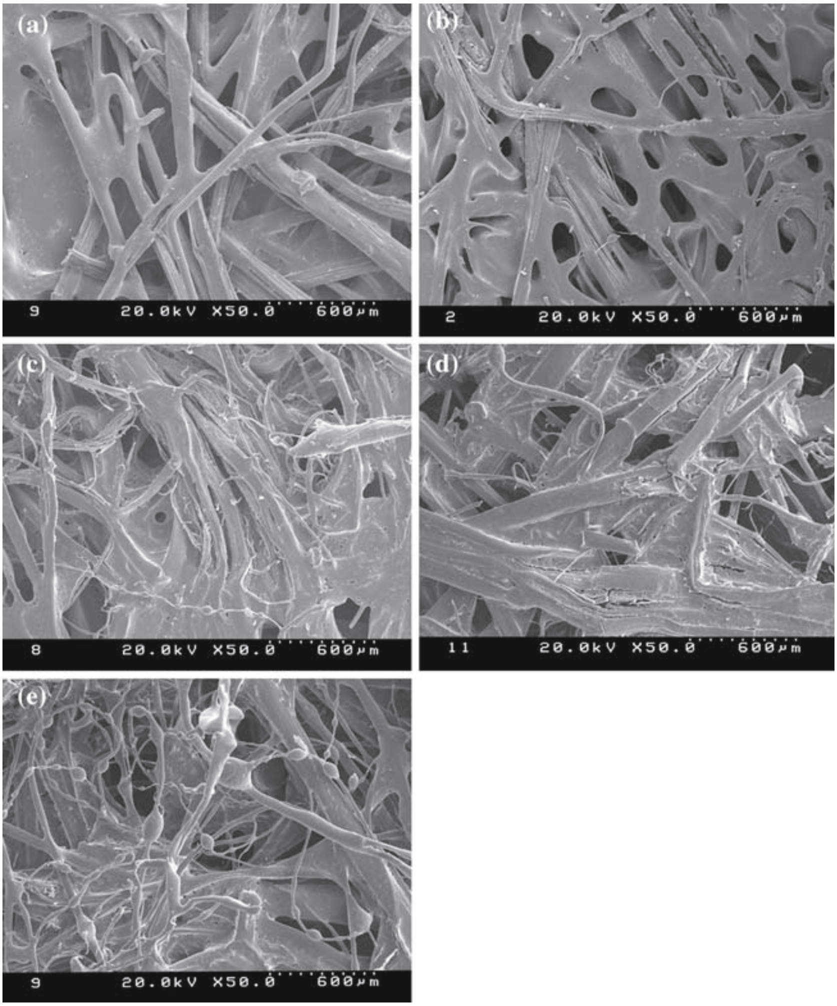

Fig. 1 Micro-photograph of the sample boards by compression molding in group C with different doses of electron beam irradiation: (**a**) 0 kGy, (**b**) 5 kGy, (**c**) 10 kGy, (**d**) 15 kGy, and (**e**) 20 kGy

moisture was evaporated and the PP was melted. A small portion of moisture remained in the samples; however, the quantitative porosity and moisture content were not considered.

Figure 1 shows a micro-photograph of the sample boards in Group C by compression with different doses of electron beam irradiation. As the dose of electron beam irradiation increases to 15 kGy, the cross-linking generated by the mixing of PP, NF, and coupling agents becomes dominant and more widespread; however, after that, the cross-linking disappears by overexposure to the electron beam.

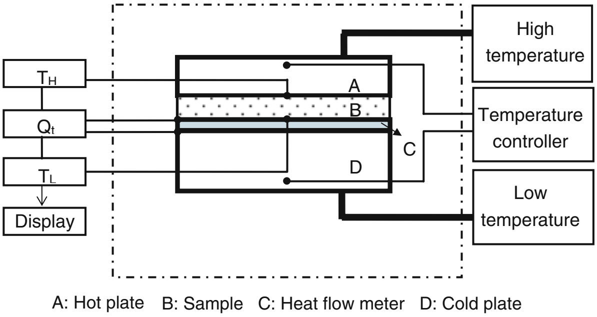

Fig. 2 Schematic diagram of heat flow apparatus for thermal conductivity measurements. A: Hot plate, B: Sample, C: Heat flow meter, D: Cold plate

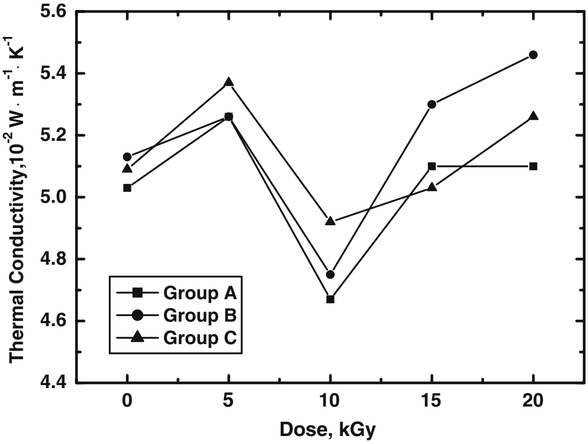

Fig. 3 Measured thermal conductivities of three groups of sample boards for different doses of electron beam irradiation

3 Experimental Results

3.1 Thermal Conductivity

The thermal conductivity of all the above samples was measured by the heat flow meter apparatus (RK-30) following ASTM-C 518 (Standard Test Method for Steady-State Thermal Transmission Properties by Means of the Heat Flow Meter Apparatus) and ISO 8301 (Thermal Insulation, Determination of Steady-State Thermal Resistance and Related Properties). A schematic of the apparatus is shown in Fig. 2. The thermal conductivity can be calculated from measurements of the temperatures, T_{H} and T_{L}, the heat flow Q_t, and the thickness of the sample [8]. The thermal conductivity of each sample was measured five times and then averaged. The sample size was $300 \times 300\,\mathrm{mm}^2$, and its thickness was 1.8–2.5 mm.

The obtained thermal conductivities are shown in Fig. 3. The measured thermal conductivities range from 4.6×10^{-2} to $5.4 \times 10^{-2}\,\mathrm{W{\cdot}m^{-1}{\cdot}K^{-1}}$. All the groups of the samples show similar trends for incremental changes in the doses of the electron beam irradiation. At first, the thermal conductivities increase and go through a local

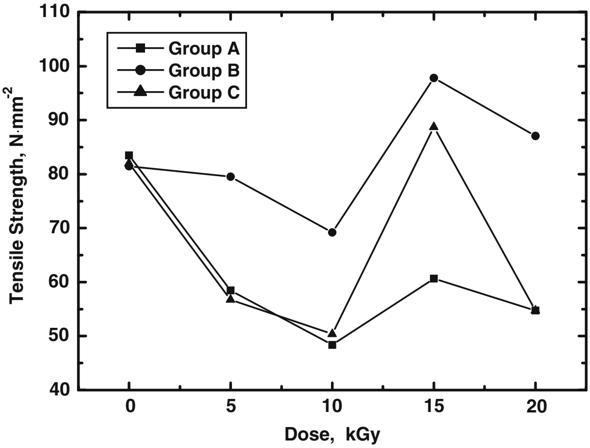

Fig. 4 Measured tensile strengths of three groups of sample boards for different doses of electron beam irradiation

maximum, when the dose is 5 kGy and then they start to decrease and go through a minimum at 10 kGy. The reason for this is assumed to be the adherence of micro-droplets evaporated from the natural fiber to the interface of the material. After that, the thermal conductivity increases and recovers initial values. The thermal conductivity depends not only on the microstructure of the material, but also on other effects, such as the porosity and moisture; therefore, more precise investigations are required to fully explain this result.

3.2 Tensile Strength

Tensile tests were performed by using an Instron Model 4206 Universal Testing Instrument. A 150 kN load cell was used, with a load weighing system uncertainty of 1.0% of reading. Five samples were prepared for each test. The size of the sample was 120 mm × 25 mm. Figure 4 shows the measured tensile strengths of the samples [9]. The results show that the tensile strengths of the three groups cover the range from 54 to 98 N·mm^{-2}, and as the dose of the electron beam increases, the tensile strength decreases and goes through a local minimum when the dose is 10 kGy and starts to increase and goes through a maximum when the dose is 15 kGy. This trend is similar to that observed for the thermal conductivity results. Group B shows the largest tensile strength.

3.3 Deformation

Figure 5 shows the measured deformation after thermal cycles ($-30\text{C} \times 2\text{h} \rightarrow \text{RT} \times 0.5\,\text{h} \rightarrow 90\text{C} \times 2\,\text{h} \rightarrow \text{RT} \times 0.5\,\text{h} \rightarrow 50\text{C}$, 95% humidity $\times 15\,\text{h} \rightarrow \text{RT} \times 0.5\,\text{h}$), repeated for three times. The negative values represent upward deformation and the positive values represent downward deformation. The values slightly changed after electron beam irradiation compared to no irradiation; however, the effect of the dose is not clear at present.

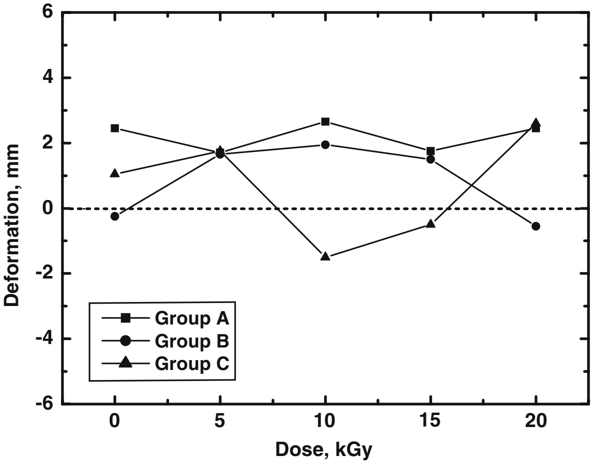

Fig. 5 Measured deformation of three groups of sample boards for different doses of electron beam irradiation after thermal cycling

4 Conclusion

In order to improve the thermal properties and mechanical properties of thermoplastics reinforced with natural fiber, samples were prepared from polypropylene, natural fiber, and coupling agents and irradiated by different doses of an electron beam. The measurements of thermal conductivity and tensile strength show that the thermal and mechanical properties were changed by electron beam irradiation. As shown in Fig. 3, the thermal conductivity becomes minimum when the dose of electron beam irradiation is 10 kGy and begins to rise as the dose increases. The tensile strength shown in Fig. 4 exhibits roughly similar trends to that of the thermal conductivity in Fig. 3. However, the effect of the electron beam on the deformation after thermal cycling was not clear as shown in Fig. 5. From these trends we can conclude that both the thermal conductivity and the tensile strength depend strongly on the strength of the bonding between the natural fiber and polypropylene. These experimental results will be utilized for enhancing energy savings in automobiles with improved designs of cooling and heating systems in a harsh environment. These thermophysical property data are very important for the thermal design of automobiles.

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