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Fatigue life and residual strength of a short- natural-fiber-reinforced plastic vs Nylon

M. Mejri [a, b], L. Toubal [a, *], J.C. Cuillière [b], V. François [b]

[a] Laboratory of Mechanics and Eco-Materials (LMEM), Université du Québec à Trois-Rivières, 3351 boul. Des Forges, C.P.500, G9A 5H7, Québec, Canada
[b] Équipe de Recherche en Intégration Cao-CAlcul (ERICCA), Université du Québec à Trois-Rivières, 3351 boul. Des Forges, C.P.500, G9A 5H7, Québec, Canada

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ABSTRACT

A new natural fiber composite made of high density polyethylene (HDPE) and short birch fibers (SBF) was developed to replace high-performance thermoplastics (Polyamide) commonly used in gears manufacturing. 3-point flexural quasi-static tests were achieved on bending specimens to assess mechanical properties. Comparison between these results and those of polyamide (PA) and neat polyethylene has showed that the polyethylene reinforced with 40%wt of SBF presents tensile and flexural mechanical properties that are higher than those of the PA11 or the neat polyethylene. After static characterisation, fatigue tests were performed to determine ε-N curves and the evolution of residual strength. Then, the fatigue behavior of the studied composite has been compared with that of PA66 and of ultra-high molecular weight polyethylene (UHMWPE). It has been noticed that polyethylene reinforced with 40%wt of SBF presents a high cycle fatigue strength (HCFS) that is more important than that of PA66 and UHMWPE. Consequently, the studied composite represents a good alternative to replace Nylon in spur gears manufacturing.

1. Introduction

Many research projects in engineering show a very high interest towards composite materials. These materials represent an essential ingredient of the design process in many sectors, including automotive, marine and aircraft industries. Over the past decades, there has been an increasing demand for natural-fiber–reinforced composites. Natural fibers present many advantages over synthetic fibers, including low density, reasonable mechanical properties, and environmental benefits [1]. These fibers come from three sources: vegetal, animal and mineral. Fibers from a vegetal origin are the most commonly used in this research field and they originate from plants or wood. These fibers are mainly composed of three constituents: cellulose, hemicellulose and lignin [2–4]. Cellulose is the main constituent of most natural fibers, and it is also the component responsible for its excellent structural properties. Cellulose is also hydrophilic, and it is the main cause of water uptake in this type of fibers. Hemicellulose is an amorphous polysaccharide, and it is partially soluble in water. Finally, lignin is a complex polymer which acts as a binder for the other components (cellulose, hemicellulose and others) in natural fibers and it is considered as a hydrophobic component.

Several research projects focused on quasi-static mechanical properties of plant fibers composites based on a thermoplastic matrix such as polyethylene or polypropylene. These studies involved tensile, flexural and impact loading [5–11]. Among these studies, Hassan et al. [7], and S. K. Nayak et al. [6] worked on the effect of fibers content on the mechanical properties of this type of composites. They have respectively shown that an increased rate of short fibers (jute and sisal) provides improved tensile and flexural rigidity of composites made with a polypropylene matrix. S. K. Nayak et al. [6] have also worked on the effect of the maleate polypropylene (MAPP) coupling agent on the mechanical properties of polypropylene reinforced with short sisal fibers. They showed that increasing the MAPP rate induces an increase of tensile and flexural moduli. In the literature, research work is also focused on the dynamic and thermogravimetric response of short plant fibers composites. We respectively mean here response in dynamic mechanical analysis (DMA) [6,12–15] and thermogravimetric analysis (TGA) [6,10,15,16]. DMA assesses storage/loss modulus and damping factor of the studied composite, while TGA help to investigate on decomposition and thermal stability of the material, under nitrogen atmosphere. Durability of plant fibers

* Corresponding author.
E-mail address: lotfi.toubal@uqtr.ca (L. Toubal).

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composites has also been studied by several authors such as Fotouh et al. [17]. They investigated the effect of short hemp fibers content on the fatigue behavior of a composite based on a HDPE matrix. Experimental results show that an increase of the fiber rate brings about an interesting increase of tensile fatigue life.

Researches about short vegetal fibers composites also investigated using wood fibers as reinforcements with polyethylene or polypropylene matrices. Several authors have characterized this type of composites in terms of quasi-static mechanical properties [18–29]. Most of these authors have investigated the influence of the fiber rate and of the coupling agent rate on tensile, flexural and impact properties. They showed that an increase in fiber or coupling agent content causes an increase of elasticity modulus and strength in the case of tensile or flexural tests. They also demonstrated that the additional use of these components in the thermoplastic matrix, increases the Charpy impact strength. Durability studies on thermoplastic matrices reinforced with short wood fibers were also carried out by several researchers. Park et al. [26], Sain et al. [30], Bledzki et al. [21] and Bravo et al. [31] studied the effect of temperature and fibers/coupling agent rates on the creep behavior of wood fibers composites. They showed that the increase of fibers/coupling agent rates and temperature respectively cause increase and decrease of the creep strength. Bledzki et al. [21] and M.D.H.Beg et al. [32] have also investigated the effect of hygrothermal aging on mechanical properties of short wood fibers composites. They found that the presence of moisture in composites induces a decrease of tensile mechanical properties and impact strength. Some other authors have studied the durability of thermoplastic matrices reinforced with wood flour by performing cyclic tests to determine the fatigue life. Yang et al. [29] showed that coupled composite, which made from HDPE, pine wood flour and coupling agent, performed better than the uncoupled composite (without coupling agent). Using these experimental results, Yang et al. [29] have proposed a new non-dimensional fatigue model which predict the fatigue life of these composites.

Despite all this research work about short wood fibers composites, the range of applications involving these materials in engineering design is still limited due to a lack of knowledge about long-term behavior of these composites, especially under cyclic loading. In this context, this work focuses on studying the flexural fatigue behavior of a promising short wood fibers composite. The objective is replacing high-performance thermoplastics commonly used in spur gears manufacturing, like Polyamide for example, by Polyethylene reinforced with 40%wt (in weight) of short birch fibers (SBF). Indeed, using this type of composites for spur gears manufacturing may allow a very significant decrease in manufacturing costs, from 5.5 CAN$/Kg (for Polyamide) to 1.6 CAN$/Kg (for Polyethylene) [25]. Moreover, using birch fibers would also bring about a reduction in the use of oil-based plastic materials. The choice of the type and rate (40%wt) of fiber is based respectively on the significant presence of birch in Canada and on results obtained by Bravo et al. [24,31]. These authors have notably shown that using 40%wt of short birch fibers, as reinforcement, brings about quasi-static mechanical properties that are similar to those of some plastic materials such as Polyamide (PA6 and PA11), better known under its industrial name “Nylon”.

This paper is organized as follows: in section 2, materials used are introduced, which is followed by a presentation of the manufacturing procedure and of the methodology applied in experimental testing. In section 3, flexural mechanical properties of polyethylene reinforced with 40%wt of SBF are measured, discussed and compared with those of some plastic materials used in spur gears manufacturing. Then, the bending fatigue life of the material is presented as a ε-N curve. This curve is plotted for two load frequencies (10 and 15 Hz). Fatigue damage of polyethylene reinforced with 40%wt of SBF is then evaluated and discussed based on the evolution of residual strength. Finally, the fatigue behavior of this composite is compared to that of classical materials as Nylon 66. This comparison is made based on ε-N curves and on the evolution of residual strength.

2. Experimental tests

2.1. Materials

The thermoplastic used in this work is high density polyethylene (HDPE Clair 2909, donated by NOVA Chemicals). Short wood fibers from white birch (TMP 20–60 mesh) were used with HDPE to manufacture composite specimens. The aspect ratio (mean length-to-mean diameter ratio, L/D) of birch fibers was 19.8, with 0.49 mm mean length and 24.7 μm mean diameter [25]. MAPE (maleated polyethylene, G2010) was used as a coupling agent in the composite material to improve quality of the interface between HDPE and short birch fibers.

2.2. Samples manufacturing

The manufacturing process used involved two consecutive steps, which are blending and molding (Fig. 1 a and Fig. 1c). Blending consists in melting polyethylene with the coupling agent on rollers at a temperature between 170 and 190 °C and mixing them with fibers. After mixing all constituents, peeling of this mixture from the roller is done before re-blending it several times. The aim of peeling and subsequent re-blending of the mixture is to ensure isotropy of the composite sheet. When blending is completed, the composite sheet is removed from the roller and it is cut into strips (using a knife) according to the molder size. The second step is molding, which consists in filling a mold with material and putting it in a thermopress at 170 °C and at a pressure of 10–15 metric tons. After 10–15 min of thermic compression, the mold is cooled to 60 °C, by circulating cold water with 43 $°C.min^{-1}$ as constant cooling rate.

Bending specimens were manufactured using 40%wt (in weight) of short birch fibers (SBF), 3% of MAPE and 57% of HDPE, according to the dimensions and geometry that are specified in ASTM-D638 and ASTM-D790 standards (Fig. 1d). The dimensions of the mold, used in the molding step, are 127 mm (length), 12.5 mm (width) and 3.3 mm (thickness).

2.3. Quasi-static bending tests

Three-point flexural tests were performed in accordance with the ASTM-D790 standard. These tests were carried out on an Instron model LM-U150 electromechanical testing machine, equipped with a 10 kN load cell (Fig. 2a). The parameters used for these tests were a 1 mm/min speed and a 55 mm distance between flexural supports. The objectives of these quasi-static bending tests were assessing quasi-static properties of polyethylene reinforced with 40%wt of SBF and comparing these properties with those of neat polyamide (Nylon) and polyethylene.

2.4. Bending fatigue tests

Flexural fatigue tests were conducted using a MTS servo hydraulic testing machine equipped with a 100 KN load cell (Fig. 2b). They were performed using sinusoidal displacement control. The displacement ratio $\left(R = \frac{\delta_{min}}{\delta_{max}}\right)$ was 0. Two loading frequencies were used in these flexural fatigue tests: 10 and 15 Hz. The objective is evaluating the effect of loading frequency on the fatigue behavior of polyethylene reinforced with 40%wt of SBF. The choice of these