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Effect of hygrothermal aging on the mechanical properties and ductile fracture of polyamide 6: Experimental and numerical approaches

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ABSTRACT

In this paper we present an experimental and numerical approaches aimed to assess the hygrothermal aging effect on the mechanical properties and ductile tearing of polyamide 6 (PA6). Conditioning was conducted at different temperatures (24 ± 3, 70 and 90 °C) and diffusion coefficients were estimated. The behavior of PA6 is discussed before and after aging. Digital Image Correlation (DIC) method was used to precise the displacement field at different steps of loading. A numerical model based on the local approach to fracture mechanics was tested to predict ductile tearing of PA6. Excellent agreement was proved with experimental results in terms of the J—Δa, load–displacement and CTOD–Δa curves.

1. Introduction

The use of polymeric materials is increasing due to their easy formability, light weight, resistance to various chemical materials. This flexibility makes them materials of the future. Thus, plastic engineering materials are continuously replacing metal parts in the manufacture of machine parts. In particular, polyamide 6 (PA6) is widely used in a variety of applications because to, among others, its low manufacturing cost, its wear resistance compared to other polymers due to its ability to form a thin and uniform transfer film while sliding against steel parts [1]. However, environmental attack by moisture can affect its mechanical properties. As polyamides are hygroscopic and eventually, they take up moisture when exposed to humid air [2]. Here, various physical (reversible processes) and/or chemical changes of modifications (non reversible processes) occur within the exposed materials. These changes, that generally depend on the environmental conditions such as exposure time, humidity and temperature, involve plasticization of the material by water, hydrolysis of the material or molecular degradation with breaking of the polymeric chains.

On the other hand, studying of natural aging is time consuming and it may take several years to obtain any result. For this reason, accelerated aging or more specifically hygrothermal aging was generally adopted in laboratory scale. Thus, the temperature and/or the atmospheric pressure of the environmental aging conditions were raised beyond the normal service conditions in order to accelerate the moisture diffusion and the degradation process. This aging confirmed to be useful and time-effective. Thereby, results will be gotten in a reasonable time. There have been numerous attempts to understand the effect of hygrothermal aging on polymers properties. Results from different studies were generally consistent with each other.

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Nomenclature

M_t	the moisture content of a sample at a given duration
W_0	the weight of dry sample
W_t	the weight of sample at a given time t (mass of wet sample)
ε	strain
ε_e	elastic strain
ε_p	plastic strain
σ	stress
σ_y	yield tensile stress
E	elastic modulus
n	hardening coefficient
k	coefficient indicating the strength
U	deformation energy
B	the thickness of the sample
W	the sample width
a	the crack length
P	load
Δa	crack growth
$J_{0.2}$	fracture toughness
R/R_0	the void growth rate
$\frac{dJ}{da}$	crack extension resistance
CTOD	Crack Tip Opening Displacement

They reported that moisture content increases significantly the molecular chain mobility due to the plasticization effect of moisture. Therefore, absorbed water acts as a plasticizer i.e. it reduces the relaxation time [3]. Thereafter, it induces plastic deformation with a lowering of the glass transition temperature (Tg) [4,5]. Since that absorbed water can affect the polymers durability and alter its properties, there has been a spate of interest on the mechanical behavior of polymers after hygrothermal aging. It has been shown that absorbed water in polyamide has a large influence on many properties including modulus and yield stress decrease while, elongation at break increases [6,7]. Aging also influences the fracture mechanical properties of the polymers [3]. It is demonstrated that moisture gained by hygrothermal aging impoverishes the fracture toughness of Nylon 12 [2]. However, from the literature review, many others researchers found that the increased polymer chain mobility which usually interpreted as a plasticization effect, and as such, it should produce an increase of fracture toughness [8].

Even though, the effect of hygrothermal aging on toughness behavior of polymers has been little investigated using a fracture mechanics approach (J-integral). In fact, several published works have used the essential work of fracture (EWF) method. In 2007, Bárány et al. [3] have found that plastic work of fracture of two polyester (PET, PETG) sheets after hygrothermal aging decreases with the aging time. The embrittlement of the polyesters, induced by physical aging associated with the increasing yield stress, the resistance to crack propagation also decrease.

Based on the aforementioned literature [6], water absorption of PA6 at temperature ranging from 40 to 60 °C increases toughness. While, the effects originated by the physical aging of poly-lactic-acid (PLA) films have shown a brittleness at room temperature [9]. Moreover, in recent works, the use of Digital Image Correlation (DIC) technique was applied to study the strain field analysis during fracture testing [10]. Hence, the DIC technique help to make optical full-field displacement/strain measurements [11].

On the other hand, computational micromechanics is emerging as a powerful tool to study the mechanical and damage behavior of materials. With the help of finite element analysis software, researchers have focused on the description of damage of PA6 [12,13]. Song and coworkers [12] have applied the Gurson–Tvergaard–Needleman (GTN) model to nylon 6 to mimic its plasticity and damage behavior. Jeridi et al. [13] have proposed a reliable constitutive models based on Mechanics of Porous Media such GTN approach that consider both mechanical and damage behavior of Polyamide 6 (PA6) and Polyamide 11 (PA11) subjected to tensile and creep loadings. In fact, an universal constitutive model which can describe damage of polymer materials under hygrothermal aging conditions is yet to be established.

Otherwise, in this work, a relative simple uncoupled model using local approach to fracture mechanics was tested to describe the ductile tearing in the case of aged and unaged PA6. Then, the proposed modified Rice and Tracey model (RTM) [14] was implemented in order to simulate the crack propagation in pre-cracked sample of tearing test.

The main motivation for this current research is to evaluate the effect of hygrothermal aging on the fracture behavior of PA6. Indeed, fracture behavior analysis of ductile polymers is based on the determination of the crack growth resistance J–R