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Fatigue behavior enhancement of short fiber glass reinforced polyamide by adding phase change materials

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ABSTRACT

High responsibility thermoplastic components subjected to dynamic forces show serious in-service thermal limitations. This paper shows that adding the adequate material with a phase-change, PCM, to a thermoplastic matrix component significantly increases its fatigue life. To do this, the fatigue resistance of short fibre-glass reinforced polyamide is analysed by means of monotonous fatigue tests on tensile specimens. Next, the design of the pieces of this material, used in high-speed rail fastenings, is optimised for fatigue efforts by means of accelerated single-piece tests. Finally, it is verified that the fatigue resistance of these pieces endowed with hydrated salt, $Na_2S_2O_3 \cdot 5H_2O$, which acts as a PCM, increases by a surprising 400% with respect to the reference pieces without PCM.

1. Introduction and aim

One of the main damage mechanisms in structural parts injected with short-fibre glass reinforced polyamides (PA) is caused mainly by the dynamic efforts of fatigue applied onto them in service conditions. An example of the damage generated by these processes appears in insulating parts, made with the mentioned material, which are used to connect the steel rails to the concrete sleepers, and to insulate them electrically, in modern railway tracks. The cause of deterioration of these insulating fastening railway parts, injected with short fibre-glass reinforced PA 6.6, is associated to the dynamic mechanical fatigue process due to the circulation of trains on the line [1,2]. The thermoplastic material of the insulating parts is subjected to fluctuating loads whose periodical repetition produces its thermal heating, changing its flexibility and mechanical behaviour. Experimental laboratory techniques were used to reproduce the fractures found in the in-service parts [3], showing that the fracture was due to fatigue processes.

To this end, it is necessary to establish the dynamic fatigue behaviour of short fibre-glass reinforced polyamide, in order to determine the causes that produce damage initiation and the conditions that govern its evolution up to the moment of fracture. From the obtained results, it will be possible to determine the failure mechanisms in fatigue that establish the in-service limit conditions of high mechanical responsibility components, made with this reinforced thermoplastic polymer. Nevertheless, the use of technical thermoplastic polymers in engineering pieces is restricted when the temperature reaches the glass transition temperature value (T_g), a characteristic of each material.

Regarding modern railway fasteners for high speed lines that incorporate engineering thermoplastic polymers, the technical specification requirements, as well as the international standards, simply provide a recommendation to make a pause in the test in order to dissipate the heat generated, to reduce the frequency of the application of alternating loads or to ventilate the system when the temperature reached could affect the correct operation of the device [4,5]. For this case, the temperature limit in any polymeric part is set at 50 °C.

This paper aims to demonstrate that besides design conditions, the controlled addition of phase change materials, adequately selected, is able to improve the fatigue behaviour of polyamide reinforced with short fibre-glass, under high temperature requirements in service. Selecting the appropriate PCM, it is possible to cool the thermoplastic matrix when the temperature is close to the glass transition temperature. Under these conditions, and as a distinct advantage, the structural integrity of the component is maintained under the action of dynamic loads, and so the fatigue

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Abbreviations

PA	polyamide
PCM	phase change material
T_g	glass transition temperature
T_M	melting temperature
σ_R	strength
σ_{max}	maximum stress
σ_{min}	minimum stress
$\Delta\sigma_6$	fatigue resistance
$\Delta\sigma$	stress variation
σ_{ap}	applied stress
LVDT	linear variable differential transformer
SEM	scanning electron microscope
N	number of cycles
ε	strain
ε_{max}	maximum strain
$d\varepsilon/dN$	strain rate
E_H	hysteresis energy
dE_H/dN	loss energy rate
DSC	differential scanning calorimeter
$d^2\varepsilon/dN^2$	strain acceleration
$\Delta\varepsilon$	strain variation
ΔT	temperature variation
ΔP_C	endurance limit

life of the reinforced polymeric parts is significantly increased. In this context, the aim of the study is to enhance the fatigue resistance of the reinforced polyamide parts by introducing the suitable phase change material in the composite. For this purpose, the hydrated salt $Na_2S_2O_3 \cdot 5H_2O$, whose melting point is established at 48.5 °C [6], has been selected in order to avoid reaching the limit temperature of 50 °C.

2. Materials and experimental techniques

2.1. Materials and test specimens

2.1.1. Short fibre-glass reinforced polyamide

Initially, this work studies the tensile fatigue behaviour of PA 6.6, reinforced with 35% of short fibre-glass by weight. The thermal properties of the polyamide used as the matrix composite are shown in Table 1. Normalised tensile strength specimens were used in accordance with the corresponding standard [7] (4 mm thickness) (see Fig. 1). They were made by injection moulding in such a way that the short glass fibres (150 μm length and 10 μm diameter) were oriented parallel to the longitudinal axis of the specimens.

2.1.2. Flanged plates

The study then focused on a high-responsibility part. This specific part is a flanged plate injected with the reinforced polyamide, used to fasten the rails to the sleepers and to maintain the gauge in high speed lines [8]. The study was performed on two evolving design geometric models, based on the substitution of large thicknesses by nerved structures. The new design (72 × 110 × 11 mm) [9], as well as offering a reduction in weight of 26% (final mass of 130 g) along with the associated reduction in cost, should at least maintain the fatigue resistance (see Fig. 2). In this case, the material is injected to keep the glass fibres oriented parallel to the direction in which the forces of the rail are produced by the passing of the trains. Finally, this optimised design part was considered in order to check whether the PCM selected is able to improve the mechanical fatigue performance of the structural piece.

Table 1
Thermal properties of the polyamide 6.6 (ASTM–D Standard).

Melting point	255 °C
Coefficient of linear thermal expansion (−40 °C to +30 °C)	$7.2 \cdot 10^{-5}$ °C^{-1}
Deflection temperature under flexural load (1.8 MPa)	75 °C
Low temperature brittleness	−84 °C
Maximum continued service temperature	75 °C

All the values measured at 50% RH.

Due to the hygroscopic nature of the polyamide and its effect on the mechanical properties, the material humidity content was controlled and established initially at 1.5% in all the cases.

2.1.3. Phase change material for flanged plates

The PCM selected must prevent the temperature of the reinforced polyamide flanged plates from surpassing the 50 °C established by the technical specification of the product. From Table 2, which presents inorganic hydrated salts with their corresponding phase-change temperatures (T_M), the compound $Na_2S_2O_3 \cdot 5H_2O$ has been selected as it is the one that best fits the thermal requirement. The characteristics of the PCM selected are shown in Table 3.

The selected PCM is based on hydrated salts, so that it should not lose its molecular water in order to maintain its phase change temperature. This fact constitutes the greatest difficulty in integrating it together with the thermoplastic polyamide matrix compound, as both should be injected at high temperature (around 290 °C) into the mould. For this reason, the process of adding the phase change material on the surface of the reinforced thermoplastic polymer piece after injection was chosen (see Fig. 3). This fact takes into account the advantage of the existing gaps in the geometry of the optimised design part, reaching a ratio of PCM in the polymer sample of 8% by weight. Then the zone occupied by the PCM was properly sealed with a thermosetting polymer based on calcium, vaseline and stearic acid, which does not affect the functional characteristics of the flanged plate.

2.2. Experimental techniques

2.2.1. Fatigue characterisation on tensile specimens

As a reference value, the strength (σ_R) was determined for the material under dynamic conditions by applying a tensile impact load onto the tensile specimen. The fatigue tests were performed on a universal mechanical testing machine under load control and

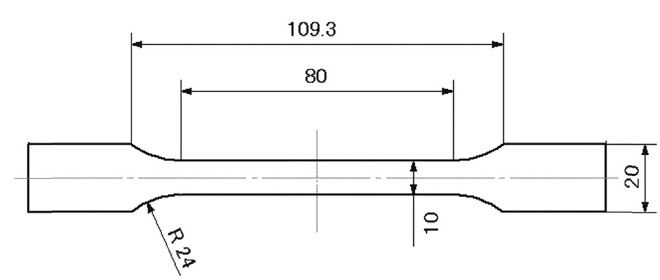

Fig. 1. Tensile specimens (units in mm).