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Rain erosion resistance of injection moulded and compression moulded polybutylene terephthalate PBT

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ABSTRACT

Offshore wind turbine rotor diameters still increase. Blade tip velocities are up to 110 m/s, giving rise to more severe raindrop impact conditions and related erosion of the wind turbine blades. In the current work droplet impingement erosion tests were performed for injection moulded and compression moulded polybutylene terephthalate PBT. The measured incubation periods were compared to an extended and improved fatigue based erosion model.

The developed erosion test set-up was based on a high water pressure nozzle system spraying water drops at a stationary PBT surface. Model results with thermoplastic materials simulating heavy rain conditions with a droplet size of 1.8 mm and an impact velocity of 120 m/s are shown. Model results with PBT materials simulating the used test conditions are shown and compared with the measured incubation periods. Although a reasonable similarity between test results and model calculations for the injection moulded PBT was found, the absolute value of the incubation period predicted by the model for compression moulded PBT differed substantially. This probably resulted from the lower confidence level of the S-N curve for the compression moulded PBT. The droplet impingement measurements and model predictions both showed a substantially higher incubation period for injection moulded PBT compared to compression moulded PBT.

1. Introduction

Today wind energy turbines with a nominal power of 5–8 MW [1] dominate the market, with an increasing proportion of larger wind energy turbines up to 9.5 MW. The rotor diameter of these multi-MW wind energy turbine systems is typically 165 m [2]. The combination of large turbine blades with tip velocities up to 120 m/s and severe rain conditions gives rise to erosion of the wind turbine blades, especially the leading edge. This reduces blade aerodynamic efficiency, and power output. Protecting the blades of large wind turbines, offshore and onshore, with rain erosion resistant materials is therefore of great economic interest.

Turbine blade manufacturers are searching for alternative blade materials to overcome engineering problems with respect to the weight and manufacturing of future blades of even greater lengths. Blades are currently made of glass fibre in an epoxy matrix, combined with a polyester gelcoat and a polyurethane coating on the outer surface [1,3]. This class of materials, however, limits the application of longer blades because of the resulting total weight. The use of glass fibre reinforced thermoplastics might overcome this because of the expected beneficial weight/performance ratio [4]. Within the scope of the current work, polybutylene terephthalate (PBT) has been selected as the matrix material. The most economical solution is the use of the matrix thermoplastic also as protective material on the outer surface. The number of papers on liquid impingement erosion of thermoplastic materials is limited and include Polyamide (PA), Low Density Polyethylene (LDPE), Polyethylene (PE), Acetal (POM), Polycarbonate (PC), Polymethylmethacrylate (PMMA), Polysulphone (PS) and Polycarbonate (PC) [5–7]. This study is the first time PBT has been assessed with respect to rain erosion resistance.

Rain impact erosion is studied through extensive screening on whirling arm rain erosion apparatus tests [8–13]. Furthermore, droplet impingement erosion tests are conducted using nozzle systems spraying water droplets on a stationary specimen surface [14–16]. This system is

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Nomenclature

A	constant in Rayleigh surface wave attenuation (MPa√mm) or elongation at fracture (%)
C_N	nozzle discharge coefficient (–)
D_h	cumulative fatigue damage per hour (h^{-1})
D_f	cumulative fatigue damage at failure (–)
E	Young's modulus of surface material
I_p	rain erosion incubation period (h)
I_r	rain intensity (mm/h)
N_i	number of fatigue cycles to failure or at level i
R	stress ratio in the fatigue test (–)
R_m	tensile strength (MPa)
S_D	fatigue limit (MPa)
S_f	material parameter in fatigue tests (MPa)
$S_{max,i}$	maximum fatigue stress at level i (MPa)
V_e	water velocity at nozzle exit (m/s)
c_R	Rayleigh surface wave velocity in a solid (m/s)
c_S	longitudinal wave velocity in a solid (m/s)
d_d	water drop diameter (mm)
d_s	diameter of the visible spot size on the specimen surface (mm)
h_{tot}	correction factor for the differences between fatigue test and rain impact conditions (–)
k_t	stress concentration factor (–)
m	material parameter in fatigue tests (–)
n	exponent for the Rayleigh surface wave attenuation (–)
n_{A1}	total number of raindrop impacts on the area A_1 (number of drop impacts/h)
n_r	radial distribution of density of drop impacts (impacts/mm h)
n_S	distribution of drop impacts as a function of stress (impacts/MPa h)
p_w	water pressure (MPa)
p_{wh}	water-hammer pressure on the specimen surface (MPa)
r	coordinate in radial direction (mm)
r_0	radial coordinate where the Rayleigh surface wave starts (mm)
r_1	radial coordinate where the maximum stress is attenuated $S_{max,1}$ (mm)
v_d	water droplet impact velocity on the specimen surface (m/s)
ν	Poisson's ratio of surface material (–)
ρ	density of surface material (kg/m^3)
ρ_w	water density (kg/m^3)

a relatively low-cost experimental research set-up which serves as an alternative to the expensive whirling arm rain erosion apparatus. A similar set-up is selected for this work as well.

In the rain or liquid impingement erosion process three phases are recognized in time [12,13,17]:

- Incubation period (in which there is no visible wear),
- Steady-state erosive wear (with a constant wear-rate),
- Final erosion phase (with a reduced wear-rate due to the high surface roughness, which was produced in the second phase).

This work focuses on the incubation period of the rain erosion process.

The main building blocks of a predictive model for the rain erosion incubation period, developed by the authors, has been published elsewhere [18]. This fatigue based model was extended in the current work and applied to thermoplastics to select an optimum candidate, with respect to rain erosion resistance, for a glass fibre reinforced thermoplastic blade material. The predictive model has been applied to thirteen thermoplastics and PBT and compared to rain erosion results of injection moulded and compression moulded PBT.

2. Experimental

2.1. Thermoplastic materials

The selected material for the samples was PBT. All samples were processed by Norner AS (Stathelle, Norway), based on Ultradur B2550 supplied by BASF. The PBT sheets were processed by two different production methods: compression moulding (PBT-I) and injection moulding (PBT-II).

2.2. Droplet impingement test set-up

Droplet impingement measurements were conducted based on a set-up that has been derived from Duraiselvam et al. [14] and Oka et al. [15]. It is based on a nozzle system spraying water drops on a stationary specimen surface. Fig. 1 shows schematically the droplet impingement test set-up.

Fig. 2a/b show details of the nozzle system and specimen location in the test set-up.

The water jet is delivered through a nozzle (type SJP 8/12/24 from Salomon Jetting Parts). The high pressure water pump, driven by compressed air, generates water pressures that can be operated between 5 and 100 MPa to feed the nozzle system. The round jet nozzle, with an exit orifice diameter d_n of 0.45 mm, creates a round spray pattern of small droplets, is able to maintain a high droplet velocity over a certain distance. The water nozzle exit velocity is estimated based on Eq. (1):

$$V_e = C_N\sqrt{\frac{2p_w}{\rho_w}} \tag{1}$$

in which V_e is the water velocity at nozzle exit, C_N the nozzle discharge coefficient ($C_N = 0.963$ for a round jet nozzle), p_w the water pressure and ρ_w the water density (estimated at 1025 kg/m^3). The water droplet impact velocity (v_d) on the specimen surface is assumed to be equal in this work to the water nozzle exit velocity (V_e). The latter because momentum estimates based on force measurements in the support of the specimen holder, see Fig. 2a, only showed a small deviation compared to the result of Eq. (1).

For the current work an operating pressure p_w = 8 MPa was selected, which resulted in an estimated mean droplet velocity of 120 m/s, equivalent to a typical blade tip velocity. The flow rate of sprayed water was verified by measuring the weight of water collected during a certain time of spraying. The selected relative flow rate η_Q was 0.48. Furthermore, the selected angle of impact was 90° and the nozzle-to-specimen distance 150 mm. The spot size on the specimen surface with a high density of drops has an estimated diameter $d_s \approx 25$ mm, see also Fig. 2b. Overall PBT specimen size was 50 × 100 mm, and a thickness

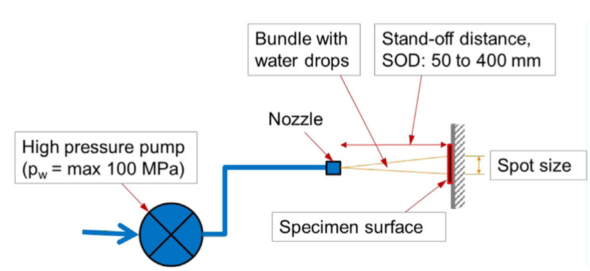

Fig. 1. Schematic overview of the TNO droplet impingement test set-up.

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