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Evaluation of a reel-to-reel atmospheric plasma system for the treatment of polymers

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ABSTRACT

Plasma treatments are widely used to enhance the surface energy of polymers prior to bonding or the application of functional coatings. This study investigates the performance of a linear atmospheric pressure plasma source for the reel-to-reel treatment of polymer webs. The continuous argon plasma treatments were carried out on 15 cm diameter polyethylene terephthalate (PET) web substrates using the linear plasma source (Plamax), operating at 13.56 MHz. The study investigated how the processing parameters influenced the effectiveness of the plasma treatment in enhancing both the polymer web's water contact angle (WCA) and surface energy (SE). Based on these measurements the plasma treatment was found to yield a homogeneous level of activation across the 15 cm web, using a treatment speed of 0.9 m/min. The plasma discharge was monitored using both thermal imaging and optical emission spectroscopy (OES). The latter demonstrated how the oxygen species which diffuse into the argon plasma due to air ingress, were directly correlated with the level of polymer activation.

1. Introduction

The surface properties of polymers are key to their performance in applications ranging from bonding, biocompatibility, coating adhesion etc. [1,2]. A range of different surface modification techniques have been used as pre-treatments in order to address the low surface energy of polymers, these include; wet chemical modifications [3], flame [4], corona [5,6], ion beam [7] treatments. Of these plasma treatments are particularly widely applied, due to their advantages such as only modifying the surface, while leaving the bulk material unaffected and due to their potential for use in continuous treatments [8]. Polymer exposure to the plasma can result in physical and chemical modifications (particularly the introduction of oxygen functionality), including etching, surface cleaning, crosslinking and activation [9–11]. These plasma treatments can be carried out using both low-pressure [12,13] and atmospheric pressure plasma systems [11,14]. Unlike treatments using low-pressure plasmas, those generated at atmospheric pressure can facilitate a more versatile treatments, which allows for the high speed and continuous processing of the substrate in the absence of a vacuum chamber [15]. A study by Donegan et al. [16] using an rf He/O_2 atmospheric plasma jet source, demonstrated that source input power had a significant effect on the degree of activation on PET. Higher input powers and longer exposure times generally result in a more rapid rate of activation.

There have been a number of publications on the use of atmospheric pressure plasmas for the reel-to-reel treatment of polymers and fibres at as outlined in Table 1. Two of these studies report on the use of an argon plasma treatments, the first by Bonandini et al. [17] investigated the effect of discharge gas composition for the activation of PET fabrics. It was concluded that the greatest improvement in wettability of the PET fabric was observed using discharged generated using Ar/He and He/O_2 gas mixtures. A study by Väänänen et al. [18] used Ar and He plasmas to activate polypropylene non-woven fabrics. Based on WCA measurements it was found that the plasma penetrated through a number of layers of the fabric. Examination of the fibres by SEM however demonstrated that over exposure of the fibres to the plasma can result in thermal damage, thus highlighting the need to maintain low surface temperatures.

In this study the performance of a 15 cm diameter linear argon atmospheric pressure plasma source called Plamax is evaluated for the reel-to-reel treatment of PET webs. The influence of source input power, source to substrate distance, treatment times and the homogeneity of the Ar plasma discharge was examined using

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Table 1
Example of studies of the use of atmospheric pressure plasma reel-to-reel processing systems for plasma treatment of polymers and natural fibres.

Author	Ref.	Type of discharge	Processing gas	Substrate
Tynan et al.	[19]	Dielectric barrier discharge	He, O_2	PE and PET
Li et al.	[20]	Glow discharge	Compressed Air	PE, PU and nylon
Bonandini et al.	[17]	Glow discharge	He, Ar, O_2, N_2/H_2, dry air	PET fibres
Nisticò et al.	[21]	Glow dielectric barrier discharge	He, O_2	PP meshes
Väänänen et al.	[18]	Dielectric barrier discharge	He, Ar	PP nonwoven fabric
Rombolà et al.	[22]	Dielectric barrier discharge	He	PP fabrics
Ceria et al.	[23]	Post-discharge	N_2	Wool fabrics

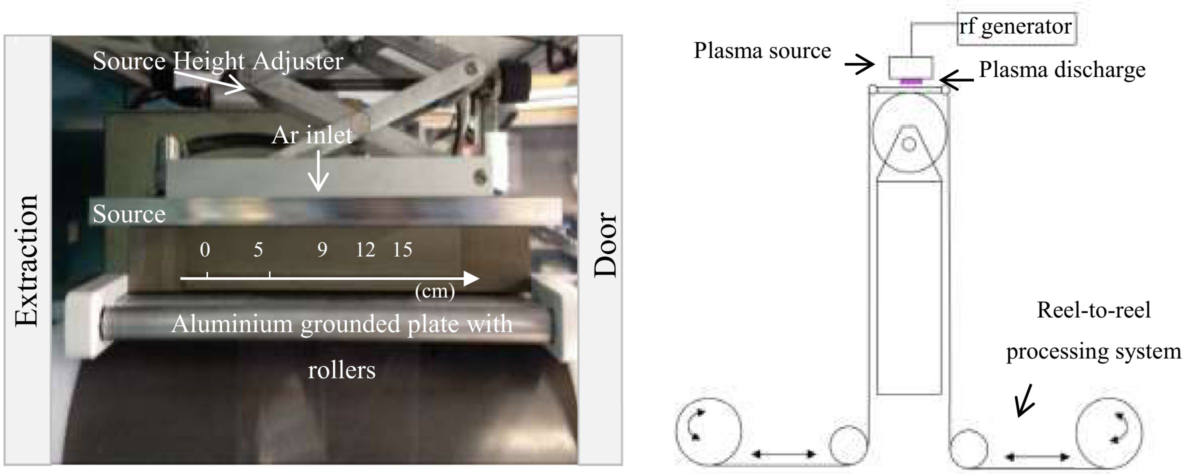

Fig. 1. Photograph of the Plamax source with ground plate mounted directly below (left) and a schematic of the reel-to-reel processing system which facilitates the movement of the web under the Plamax source (right).

thermal imaging and optical emission spectroscopy (OES). The latter technique was used to investigate if there was a correlation between the surface energy of the plasma treated polymer and the active species present in the discharge

2. Experiment and materials

2.1. Atmospheric pressure plasma source

The 13.56 MHz Plamax atmospheric plasma source was manufactured by SPS Co. Ltd. (South Korea) [24]. This source was assembled with a custom-made plasma generator head and connected to an Advanced Energy 13.56 MHz supply which is incorporation with an L-C matching unit. Input powers of up to 200 W could be supplied to the source. The Plamax source was mounted onto a reel-to-reel system which facilitated the handling of polymer substrates. A photograph of the source along with a schematic of the system is given in Fig. 1. The source counter electrode was a grounded aluminium plate with dimensions of 37 cm (L), 12 cm (W) and 1 cm (H). Two rollers were incorporated onto either side of the plate to prevent snagging of the PET web as it passes underneath the plasma discharge. This in turn was integrated into a reel-to-reel web handling system as shown schematically in Fig. 1. The plasma treatment area was 15 cm in length and approx. 1 cm in width. As ozone and other species are generated using atmospheric plasma an extraction system is required, this was mounted just to the left of the source shown in the photograph given in Fig. 1. The source orifice to grounded aluminium substrate distance was varied between 2 and 4 mm using a manual height adjustment system. The speed of the reel-to reel webs could also be adjusted and in this study web speeds of 0.9 to 1.3 m/min. were investigated.

2.2. Materials

Plasma treatment studies were carried out on PET web with thickness of 0.8 mm and width of 150 mm. 20 mm × 20 mm test samples were taken from this web for surface energy and contact angle characterisation.

2.3. Water contact angle (WCA) and surface energy measurements

WCA were determined using a Dataphysics Instrument OCA 20 system, using the sessile drop technique. The contact angle measurements were calculated using the digital images of the droplets on the substrate, these were imaged using a charged couple device (CCD) camera. Surface energy calculations were determined using three different liquids: deionised water, diiodemethane and ethylene glycol. The liquids were selected to calculate the polar (water) and dispersive forces (diiodemethane) on the surface. The droplets (1 µl) was allowed to rest on the surface for approx. 5 s before contact angles were measured. The Owens–Wendt–Rabel–Kaelble (OWRK) method was used to measure the water contact angle and surface energy of plasma activated polymers [1,25]. The WCA and SE measurements of the polymer web were taken at five positions (0, 5, 9, 12, 15 cm) along the PET web as shown in Fig. 1.

2.4. Thermal measurements

Infra-red thermal imaging of the ground aluminium plate mounted 2 mm below the plasma source were obtained (in the absence of the polymer web) using an InfraTec VarioCAM high resolution thermographic camera. The instrument has a spectral range of 7.5–14 µm in the 0–100 °C [12]. The thermal images were obtained in real time, using IRBIS software.