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Studies on the use of the coaxial plasma bulb for enhanced wettability of aluminum and polymethylmethacrylate surfaces

Julie Anne S. Ting [a,*], Leo Mendel D. Rosario [a,b], Henry V. Lee Jr. [a], Henry J. Ramos [a], Roy B. Tumlos [a,c], Reinhard V. Fischer [d]

[a] *Plasma Physics Laboratory, National Institute of Physics, University of the Philippines, Diliman, Quezon City 1101, Philippines*
[b] *Sciences Department, College of Arts, Sciences and Education, FEATI University, Sta. Cruz, Manila 1003, Philippines*
[c] *Department of Physical Sciences and Mathematics, College of Arts and Sciences, University of the Philippines, Manila 1000, Philippines*
[d] *IBF Electronic GmbH & Co. KG, Ober-Ramstadt 64372, Germany*

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ABSTRACT

The use of a short coaxial plasma line termed the “plasma bulb” has been investigated for enhancement of the wettability of aluminum (Al) and polymethylmethacrylate (PMMA) surfaces. In comparison with other plasma lines, the plasma bulb uses a single magnetron for microwave generation that could produce plasma for surface treatment. For the treatments of Al and PMMA surfaces, various plasma parameters including gas filling pressure, microwave power and treatment time were investigated for different working gases: argon, oxygen and air. Based from contact angle measurements, the largest increase in the wettability of Al (93.8%) and PMMA (76.2%) samples were obtained using air plasma for 5 min and 10 min treatment time, respectively. AFM and EDX results reveal that increased root-mean-square roughness and possible generation of oxygen-containing groups on the surface are the dominant factors contributing to the enhanced wettability.

1. Introduction

Presently, there exists a demand for surface pre-treatment of metals, polymers and composites to improve bonding with most adhesives and paints. Often these materials do not have good adhesion properties, unless some form of surface treatment is involved [1–5]. In metals, surface preparation generally consists of several processes: initial cleaning to remove surface contamination, chemical etching to remove inhomogeneous oxides formed by thermal exposure, and chemical or electrochemical treatment to promote adhesion [6]. These processes not only involve multiple cycles but also have considerable variable costs. Most polymers tend to have low wettability and poor adhesion and needs to be similarly pre-treated [2]. The performance of metals and polymers can be improved by surface modification using plasma treatment.

Plasma treatment can chemically and physically alter the natural characteristics of metal and polymer surfaces to enhance wetting properties. It is effective and environmentally-safe with simple batch process control that can easily be integrated in production lines [1,4,7,8]. As such, it has found numerous large-scale applications in the automotive, aeronautic and microelectronic industries [5,9]. One such plasma treatment system involves “coaxial plasma lines” which are used for wide-area processing of various materials. It consists of an inner conductor inside a dielectric tube. Low pressure plasma is ignited using microwaves generated by one or more magnetrons [10,11]. More homogeneous plasma is produced for surface modification by providing two magnetrons that deliver microwave at both ends of the dielectric tube [12]. In a study by Liehr et al., an array of microwave plasma lines which is operated with two power sources was used for large area thin film deposition on ceramic substrates. It was found that deposition of SiO_2 films was influenced by varying gas flow rates, pressure and microwave power [11]. Another study by Behm et al. also employed four duo plasma lines operating at 2.45 GHz frequency to functionalize the surface of polypropylene substrates for enhanced coating adhesion [13].

A modification in the configuration of plasma lines is discussed by Hübner et al., in which microwaves are supplied by a single 1.2 kW magnetron from only one end of the dielectric tube. Optical emission diagnostic methods of the coaxial linear microwave discharge have shown that this type of plasma line provides stable and homogeneous discharge with higher electron density and electron temperature at lower gas flow rates [14]. Moreover, the configuration of the plasma line also allows samples to be placed

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* Corresponding author.
E-mail addresses: julieanneting@gmail.com, jasting16@yahoo.com (J.A.S. Ting).

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perpendicular to the length of the dielectric tube to further maximize area during surface treatments.

In this study, a short plasma line termed as the plasma “bulb” is employed to modify Al and PMMA surfaces to improve wettability. A set of plasma parameters (gas filling pressure, microwave power and treatment time) was varied for different working gases (argon, oxygen and air) to determine the best discharge conditions to enhance surface wettability.

2. Methodology

2.1. Sample preparation

Aluminum (Al) (5 cm × 5 cm × 1 mm) and polymethylmethacrylate (PMMA) (5 cm × 5 cm × 3 mm) were used as metal and polymer samples, respectively. The aluminum is initially polished successively using sandpaper with grades 280, 600 and 1000, then, washed using deionized water. On the other hand, due to the soft surface of PMMA, polishing was not implemented to prevent scratching, and embedding of abrasive particles on the surface.

2.2. Coaxial plasma bulb

The coaxial plasma bulb is developed by IBF Electronic GmbH & Co. KG, Ober-Ramstadt, Germany. It is composed of a 2.45 GHz magnetron with 2.0 kW continuous wave output, the waveguide assembly and the tuning systems as shown in Fig. 1. The tuning system includes the three-stub tuner, coaxial transition antenna and sliding short. One end of the coaxial antenna is found inside the vacuum chamber, and is enclosed by a quartz glass dielectric tube. Microwaves generated by the magnetron propagate via the coaxial transition antenna to the vacuum chamber where the plasma is generated. In addition, the vacuum system is composed of two rotary pumps connected in series. The system is cooled using a Riedel PCM 15K recirculating chiller.

2.3. Plasma treatment

Al and PMMA samples were placed on a metal holder positioned below the coaxial bulb inside the vacuum chamber. Using two rotary pumps, the pressure in the chamber was lowered to a base pressure of 3.6 Pa.

Treatment of the samples was done for varying discharge conditions including gas filling pressure (10, 30, 50, 100, 300 and 500 Pa), forward microwave power (500, 1000, 1500 and 2000 W) and plasma treatment time (0.5, 1, 5, and 10 min) for different working gases (argon, oxygen and air at a distance of 30 cm from the tip of the coaxial plasma bulb. After the treatment, the samples were given five minutes to cool until the temperature is around 25 °C before subjected to contact angle measurements.

2.4. Characterizations

Changes in the wettability of the sample surfaces were determined by contact angle measurements using Dino-Lite Digital Microscope Premier and DinoCapture 2.0 software. Deionized water (DI) was used as test fluid for all measurements, and was dropped onto the sample surface using a 1 mL syringe. Uniformity of the treatment based on five different points to cover the sample area (5 cm × 5 cm) was determined for each of the three trials using contact angle measurements. The average was considered as the final contact angle of the samples.

The surface roughness and elemental composition of the samples before and after plasma treatment were analyzed using an NT-MDT Solver atomic force microscopy (AFM) and JEOL JSM-5310 elemental dispersive X-ray (EDX), respectively. AFM images were taken for a sample size of 30 × 30 μm^2. For the non-conducting PMMA, samples were initially gold-coated using JEOL JSM-1200 fine coater for 30 s.

3. Results and discussion

3.1. Variation of discharge conditions

The treatment conditions such as the gas filling pressure, forward power and treatment time for each working gas were studied based on contact angle measurements. Prior to plasma treatment, Al and PMMA samples have average contact angles of 57.9° and 54.2°, respectively.

In Fig. 2, the effects of plasma on the metal and polymer surfaces treated at 1000 W forward power and 30 s treatment time are shown. A general decrease in the contact angles was noted between 10 and 100 Pa, followed by an increase in the contact angles for higher gas filling pressures of 300 Pa and 500 Pa. In the case of Al [Fig. 2(a)], instability of the plasma at higher gas filling pressures

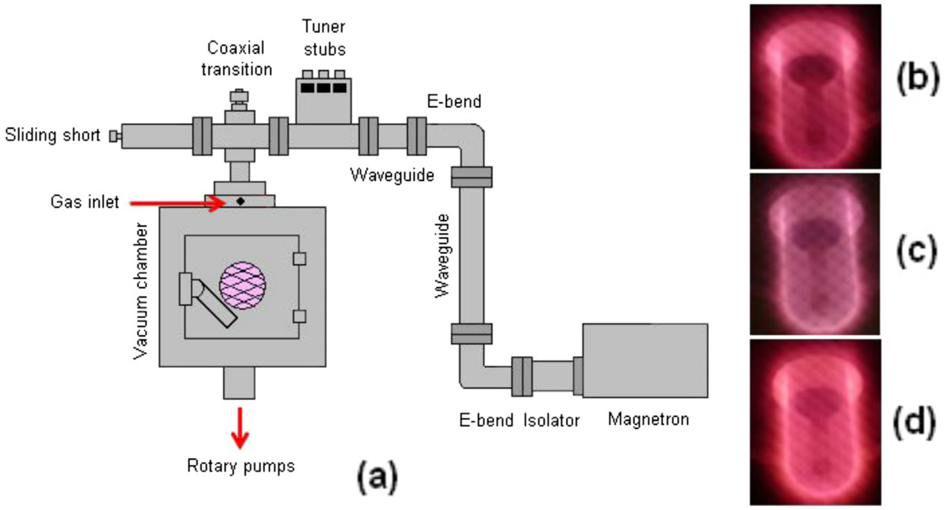

Fig. 1. (a) Schematic diagram of the coaxial plasma bulb device. Actual images of (b) argon plasma, (c) oxygen plasma and (d) air plasma.