Applied Surface Science 256 (2009) 876–883

Contents lists available at ScienceDirect

Applied Surface Science

journal homepage: www.elsevier.com/locate/apsusc

Effects of reactive gas on shear and fracture behaviors of plasma-treated polyethylene/steel joints

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ARTICLE INFO

Article history:
Received 30 June 2009
Received in revised form 20 August 2009
Accepted 23 August 2009
Available online 28 August 2009

Keywords:
High-density polyethylene
Plasma treatment
Shear strength
Fracture toughness

ABSTRACT

For this study, we investigated the effects of reactive gases (oxygen, nitrogen, and argon) on the shear behavior and fracture toughness of HDPE/steel joints by treating high-density polyethylene (HDPE) with plasma using a microwave method. We also investigated the effect of plasma treatment on the physical and chemical changes on the surface of HDPE. HDPE/steel joints were fabricated using a secondary bonding process. The results showed that the shear strength and fracture toughness of HDPE/steel joints treated with different reactive gases were ordered as follows, oxygen > nitrogen > argon. Specifically, the shear strength and fracture toughness of oxygen plasma-treated HDPE/steel joints were approximately 7600% and 2400% greater, respectively, than that of untreated HDPE/steel joints. The improvements in shear strength and fracture toughness are attributed to increase in surface roughness and the creation of carbonyl functional groups on the HDPE surface via plasma treatment.

1. Introduction

High-density polyethylene (HDPE) has unique properties including chemical resistance, light weight, and superior mechanical strength. For this reason, many studies have attempted to apply HDPE for use as a single structure and matrix material in particle or fiber-reinforced composites [1–5]. However, HDPE is a hydrophobic material, and improving its adhesion properties by use of either a physical or chemical method is required. Several methods have been reported to make HDPE more hydrophilic. Currently, plasma treatment is widely used because it can easily create new functional groups that are difficult to obtain by other methods [6–9]. Plasma treatment of polymer materials is affected by which reactive gas is used for the treatment. For example, oxygen plasma is very effective for hydrophilic modification due to formation of oxygen functional groups [10]. Nitrogen plasma is also effective for surface modification due to formation of nitrogen functionalities such as amino and amido groups [11]. Argon plasma is also used as a pre-treatment for plasma-induced grafting or for cross-linking of molecules in polymer surfaces [12–14].

Rhee et al. [15] studied improvement in fracture toughness of adhesively-bonded carbon fiber reinforced plastic (CFRP)-aluminum joints. Shenton et al. [16] performed research on the adhesive enhancement of polymer surfaces by inert atmospheric plasmas treatment, and showed that reactive and inert atmospheric plasma rapidly impart adhesion enhancement by a factor of 2–10 as measured by 180° peel tests. Moon and Jang [17] investigated mechanical interlocking and wetting at the interface between argon plasma treated UHMPE fiber and vinylester resin, and reported that argon plasma treatment of the ultra-high molecular polyethylene (UHMPE) fiber modifies the UHMPE fiber surface to be chemically more inert and that these chemical modifications reduce the efficiency of mechanical interlocking between UHMPE fiber and vinylester resin. Leroy et al. [18] and Arpagaus et al. [19] studied the wettability of HDPE powder after surface treatment. The result showed that optimal wettability was obtained by the addition of 0.75% of O_2 in the nitrogen plasma gas and the mixed O_2/Ar gas showed optimal results, respectively. XPS results indicate the formation of functional groups, and total surface free energy increased from 31.2 to 45 mN/m. Many studies have been done to investigate the surface modification of polyethylene. Ogawa et al. [20] observed the effects of functional groups and surface roughness on interfacial shear strength with UHMWPE fiber and polyethylene. Few efforts have been made, however, to improve the mechanical properties of HDPE joints by increasing adhesion strength between HDPE and the reinforcing material.

We performed surface treatments of HDPE using oxygen, nitrogen, and argon plasma to improve the shear strength and

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doi:10.1016/j.apsusc.2009.08.076

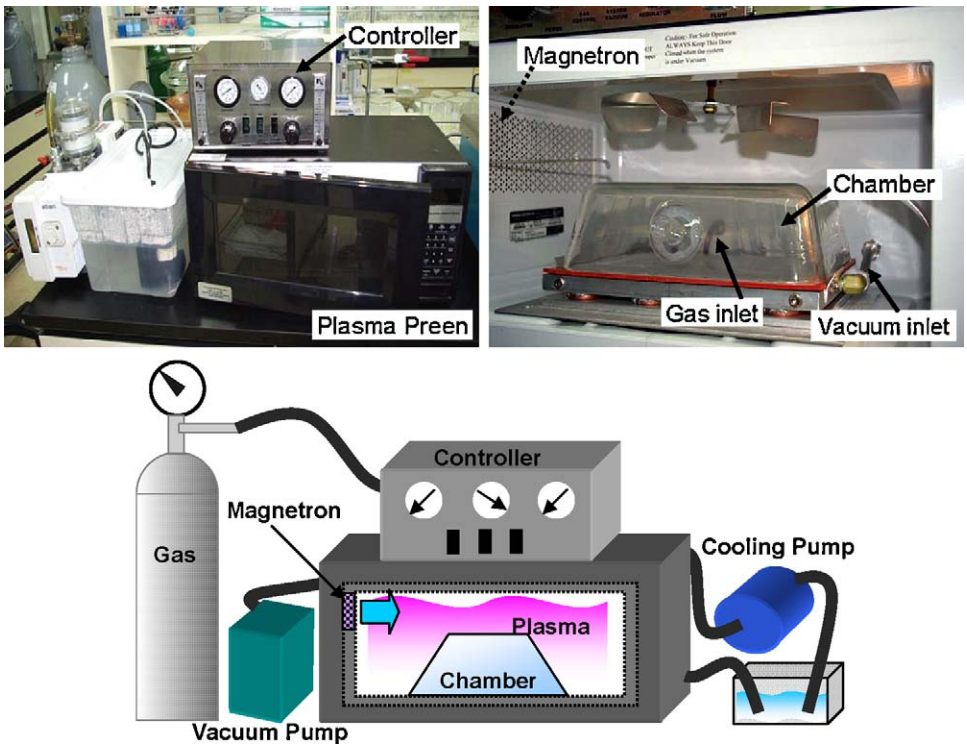

Fig. 1. Photograph and schematic diagram of the plasma apparatus.

fracture toughness of HDPE/steel joints. HDPE/steel joints were fabricated using HDPE and a steel plate, with and without plasma treatment. The effects of reactive gas in the plasma treatment on the shear and fracture behaviors of HDPE/steel joints were investigated. After the tests, this was further confirmed by physicochemical characteristic studies of untreated and plasma-treated HDPE samples by field emission scanning electron microscope (FE-SEM), atomic force microscope (AFM), attenuated total reflection fourier transform infrared (ATR-FTIR), and X-ray photoelectron spectroscopy (XPS) analysis.

2. Experimental

2.1. Materials and surface modification of HDPE

The materials used were HDPE (4000B, Honam Petrochemical Corporation, Korea) and hot-rolled mild steel plates (SS41). Prior to plasma treatment, HDPE and the steel plate were surface-cleaned with supersonic waves for 5 min each, using acetone, ethanol, and distilled water to remove surface impurities. After purification, plasmas of oxygen, nitrogen, and argon gases were introduced onto the surfaces of HDPE plates using plasma preen cleaner (U0050725A, Plasmatic Systems Company, USA) by microwave. A rectangular glass bottle (Pyrex) of dimensions of approximately 228 mm × 177 mm × 76 mm was used as the chamber. A power supply (115 V ac 15 A) was connected to the flow meter with needle valve, vent valve, time control, and duty cycle control reaction chamber. A Vacuum pump (Model 205SDMLAM) with 4 lbs was used with non-combustible oil, anti-suck back valve, oil mist eliminator, and all fittings and universal motor. To prevent heat damage of sensitive parts, water recalculating unit was used. The treatment conditions included a vacuum chamber pressure of 28 kPa, gas pressure of 0.133 kPa, power of 420 W, and a frequency of 2.45 GHz. The flow rate of each gas was 2.5 $SCFH^{-1}$ (standard cubic feet per hour). HDPE was exposed to each plasma gas for 5 min. After the plasma treatment, in order to maintain the optimal treatment condition, we performed bonding process within 10 min for each sample. Photograph and schematic diagram of the plasma apparatus are shown in Fig. 1.

2.2. Specimen preparation

To fabricate single lap shear (SLS) and cracked lap shear (CLS) HDPE/steel joints, an adhesive was prepared by mixing an epoxy resin (YD-115, Kukdo Chemical, Korea) with a hardener (D-230, Kukdo Chemical, Korea) in a ratio of 2:1. In the case of the SLS specimen, HDPE and the steel plate machined as 120 mm × 20 mm × 2 mm were adhesively bonded to each other with an adhesion size of 20 mm × 20 mm. A tab 2 mm in thickness, which was equal to the specimen thickness, was attached on the edge of each specimen to minimize the bending moment due to an eccentric load. In the case of CLS test specimens, an initial crack was made by inserting a Teflon film (thickness 0.2 μm) at the interface between the lap and the strap. The initial crack length was 24 mm, while the lengths of lap and strap were 80 and 120 mm, respectively. The adhesive joints of both specimens were cured at room temperature under a pressure of 5 kg/cm^2. Then, the joints were post-cured at 60 °C for 6 h in an oven. Schematic diagrams of the SLS and CLS test specimens are shown in Fig. 2.

2.3. Shear and fracture tests

Shear and fracture tests were performed using a universal testing machine (Instron 8871 and 8500, USA) at room temperature by applying a displacement-controlled condition. The rates of displacement applied to the SLS and CLS specimens were 0.2 and 0.5 mm/min, respectively. Also, at least three tests were performed for each case to ensure reliability of the test results.

3. Results and discussion

In a previous study [21], we showed that oxygen plasma treatment for 5 min yielded the most effective contact angle, and therefore, in this study, 5 min was applied as a treatment time for