Applied Surface Science 317 (2014) 405–413

Contents lists available at ScienceDirect

Applied Surface Science

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

Heat treatment effect on erosion behavior of poly(methylmethacrylate) for optical transmittance efficiency

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ARTICLE INFO

Article history:
Received 21 April 2014
Received in revised form 14 August 2014
Accepted 21 August 2014
Available online 28 August 2014

Keywords:
PMMA
Fresnel lens
Optical transmittance
Heat treatment
Solid particle erosion

ABSTRACT

Influence of heat treatment on optical transmittance of poly(methyl methacrylate) (PMMA) samples was investigated under solid particle erosion. Heat treatment was employed at 85 °C for 1, 2 and 3 h. Effect of heat treatment on physical, chemical, mechanical and thermal properties of PMMA samples was investigated by differential scanning calorimeter (DSC), thermogravimetric analysis (TGA), Fourier transform infrared (FTIR) spectroscopy, Vickers microhardness measurement methods. After these analysis, both pristine and heat treated PMMA samples were eroded at 15°, 30°, 45°, 60°, 75° and 90° impingement angles. Then, optical transmittance of all eroded PMMA samples was inspected by a UV–Vis spectrometer. Scanning electron microscopy (SEM) was used to explain the erosion mechanisms and to compare the roughness and optical transmittance of eroded PMMA surfaces.

Heat treatment under glass transition temperature of PMMA increased the T_g and hardness values. According to erosion test results, both pristine and heat treated PMMA samples were showed ductile erosion behavior. However; maximum and minimum optical transmittance values of eroded pristine PMMA samples were obtained for the angles of 15° and 90°, respectively. A positive effect of heat treatment on optical transmittance of PMMA was obtained for all impingement angles, but most pronounced effect was seen for 15°.

1. Introduction

In concentrated solar energy applications, Fresnel lenses recently have been one of the best choices to focus sun light onto high efficiency multifunction cells because of the advantages such as small volume, light-weight, mass production with low cost as well as effectively increase the energy density [1,2]. These lenses have traditionally been manufactured out of poly(methylmethacrylate) (PMMA) by hot embossing, casting, extruding, laminating, compression molding, or injection molding [2–4]. PMMA which is widely used in optical components is a typical transparent amorphous polymer with special features like light weight, good flexibility, high strength, resistance to corrosion, excellent dimensional stability and light transmittance [5,6]. High durability of the Fresnel lens is necessary to ensure sufficient transmission of sunlight to the cell. The surface roughness is inversely related to the optical performance which is the primary tribological concern. This concern is especially serious where the Fresnel lenses are subjected to long term exposure in a severe outdoor environment in which the surface may easily be eroded over time by aerosols which are attributed to various sources, such as soil elements lifted by the wind, volcanic eruptions, vehicle movement and pollution [7,8].

Solid particle erosion is a process of progressive removal of material from a target surface due to the repeated impact of solid particles [9,10]. Solid particle erosion generally leads to negative effects, such as wear of components, surface roughening and degradation which affect light transmittance, macroscopic scooping appearance, and functional life of the structure. These side effects can be considered as serious problems, because they are responsible for many failures in engineering applications [10,11]. Study related to the general problem of “solid particle erosion of PMMA” may be found in Ref. [12]. In this study, the general conclusion is that although a great amount of work has already been devoted to this problem, but many questions are still open. It is known that solid particle erosion is affected by many factors such as: the properties of impacting solid particles, (size, shape, density, hardness and fracture toughness); the properties of target material (hardness, fracture toughness and surface state), and the test conditions (impact speed, impact angle and ambient temperature). Among all these properties, the hardness values (*HV*) is main property influencing the solid particle erosion [13]. Therefore, it is very

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http://dx.doi.org/10.1016/j.apsusc.2014.08.119
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Table 1
Properties of PMMA sheet [25].

	Test method	Units	Value
Mechanical properties			
Density	DIN53479	g/cm^3	1.19
Poisson ratio to 20 °C	–	–	0.39
Optical properties			
Light transmittance	DIN5036	%	92
Refractive index	DIN53491	–	1.492
Electrical properties			
Dielectric strength	DIN53481	KV/mm	20–25
Transverse resistivity	DIN53482	Ohm cm	>10^{15}
Dielectric constant	DIN53483		
(a) to 50 Hz		–	3.7
(b) to 1 MHz		–	2.6
Thermal properties			
Coefficient of linear expansion	DIN52328	Mm/m °C	0.065
Thermal conductivity	DIN52612	W/m °C	0.17
Specific heat	ASTM C 351	J/g °C	1.32
Insulation coefficient, K	DIN4701	W/m^2 °C	5.1
Max. continuous service temperature	–	°C	85
Max. linear shrinkage after heating, thickness ≥ 3 mm	–	%	2

valuable to study the solid particle erosion resistance of PMMA and to find methods for improving its hardness.

For the use of PMMA as a Fresnel lens material, the optical transmittance, as well as the long-term behavior under solid particle erosion condition is of great importance. Several methods of PMMA modification are used to achieve the desired surface properties with unchanged internal structure and then, unchanged bulk properties [14–21]. Lin and Lee [22] investigated the optical transmittance behavior of PMMA under irradiation conditions and Lu et al. [23] investigated the recovery of the optical transmittance of irradiated PMMA at elevated temperatures. On the other hand, Lu and Lee [24] investigated the hardness change induced by gamma irradiation in PMMA. They reported a hardness decrement with increment of both annealing temperature and irradiation dose. However, intensive research concerning the hardness improvement that can enhance the optical transmittance under solid particle erosion conditions has not been conducted. Therefore, the present study investigated the heat treatment effect on the optical transmittance behavior of PMMA under the solid particle erosion conditions.

2. Experimental

2.1. Material

PMMA sheets commercially named “Altuglas® CN” with a nominal thickness of 4 mm were selected as test material. Table 1 gives the mechanical, optical, electrical and thermal properties of PMMA test samples according to the manufacturer’s declaration [25]. The test samples were prepared in 50 mm × 50 mm by cutting out from PMMA sheets of 400 mm × 400 mm. And then, they were heat treated at 85 °C for 1, 2 and 3 h in an electrical furnace as suggested by “Altuglas® CN” sheet manufacturers. Heat treated samples were then left to cool down naturally in the furnace, to avoid fresh stresses due to thermal shock.

2.2. Thermal analysis

Differential scanning calorimeter (DSC) measurements were performed on TA Instruments DSC Q200 calorimeter to analyze the change in glass transition temperature (T_g) with the effect of heat treatment. Samples were prepared as approximately 10 mg and sealed in aluminum pans. DSC measurements were carried out at a heating rate of 10 °C/min from 25 °C to 300 °C under a nitrogen gas flow.

The thermogravimetric analysis (TGA) of both pristine and heat treated PMMA samples were carried out by TA Instruments Q50 TGA equipment. The samples about 10 mg were heated from ambient temperature to 500 °C at a heating rate of 20 °C/min under a nitrogen atmosphere with flow rate of 50 ml/min. The temperature at 10 wt% loss (T_{10}) was taken as the onset of degradation. And also the maximum degradation temperature (T_m) was determined as the peak maximum obtained by the first order derivative weight curve.

2.3. Microhardness test

Microhardness measurements were carried out at room temperature (23 °C) using a Vickers diamond attached to Zwick ZHV10. This instrument has an automatic reading system for microhardness measurements that automatically measures the diagonal length for an indentation based on the indentation image of the test piece surface during the test. For microhardness measurements of both pristine PMMA and heat treated PMMA samples, indenter was penetrated the sample surfaces at a given load of 1.961 N for 10 s. Each sample was measured five times and the average result was taken as the reported microhardness value.

2.4. Infrared spectroscopy

The IR spectra of both pristine and heat treated PMMA samples were recorded by a Fourier transform infrared (FTIR-Thermo Nicolet Instruments) in the wave number of between 500 and 4000 cm^{-1}.

2.5. Solid particle erosion test

Fig. 1a shows a schematic illustration of the erosion test rig which was used in this study. Sharp-edge alumina (Al_2O_3) particles with a size of 120 mesh (Fig. 1c) were used for erosion test. Because it was decided that, harsh effects of wind inclusions could be simulated by these particles with known high hardness (≈20 GPa) [26]. Scanning electron microscope (SEM) photo of alumina particles was given in Fig. 1b. Alumina particles were driven by a static pressure of 1.5 bar after acceleration along a nozzle with 50 mm length and 5 mm diameter. Nozzle to sample distance was adjusted as 120 mm. Impingement velocities of erodent particles were measured with