Radiation Physics and Chemistry 145 (2018) 11–18

Contents lists available at ScienceDirect

Radiation Physics and Chemistry

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

Effect of gamma irradiation on the structural, mechanical and optical properties of polytetrafluoroethylene sheet

M. Mohammadian-Kohol, M. Asgari, H.R. Shakur*

Department of Physics, Faculty of Science, Imam Hussein Comprehensive University, Tehran, Iran

ARTICLE INFO

Keywords:
Polytetrafluoroethylene
Gamma-irradiation
Chemical structure
Mechanical parameters
Optical properties

ABSTRACT

In this study, the effects of gamma radiation on the chemical structure, mechanical and optical properties of polytetrafluoroethylene (PTFE) sheet were investigated with various doses up to 12 kGy. The chemical changes in the structure were studied by FTIR spectroscopy. Also, effects of radiation on the different mechanical parameters such as Young's modulus, toughness, strain, and stress were studied at the maximum tolerable force and the fracture points. Furthermore, changing the various optical parameters such as absorption coefficient, Urbach energy, optical band gaps, refractive index, optical dispersion parameters and plasma resonance frequency were studied by UV–visible spectroscopy. Formation of a band at 1594 cm^{-1}, which was belonged to double carbon bonds, indicated that chain-scission was occurred at 12 kGy gamma irradiation dose. As well, the mechanical results showed an increase in the elastic behavior of PTFE sheets and a decrease in the plastic behavior of it with absorbed dose increasing. Moreover, the results showed that gamma irradiation can effectively change the various optical properties of PTFE sheets due to different phenomena such as degradation of the main chains, occurring chain-scission, formation of free radicals and cross-linking in the polymer structure.

1. Introduction

There are a significant amount of gamma radiation in the nuclear sites and outside of the earth's atmosphere due to presence of different radioactive sources and occurring various phenomena such as gamma-ray bursts (GRBs). Therefore, effects of absorbed radiation dose on the performance of common materials are widely studied by a large number of researchers (Ahmed et al., 2012; Alwan, 2011; El-Diasty and Bakry, 2009; Fares, 2012; Ol'khov et al., 2012c; Prasad et al., 2011; Sharma et al., 2007).

polytetrafluoroethylene (Teflon) was widely applied in the nuclear and aerospace industries such as various types of fireproof cables, missile boards, gasoline pumps, equipment of aerospace, astronaut's outer cover clothing, heat shields of spacecraft, nose cone, fuel tanks, pressure hose and etc. Also, porous Teflon shows exceptional levels of visible spectrum reflectivity making it an ideal material for many optical applications such as a diffuser, reflector and etc. So far, many literatures have been reported about the effects of radiation on the various properties of Teflon (Allayarov et al., 2007, 2013, 2014; Forsythe and Hill, 2000; Matsumae et al., 1958; Meyer et al., 2004; Ol'khov et al., 2012a, 2012b; Olkhov et al., 2011, 2014; Oshima et al., 2001; Tabata et al., 2001). Morover, radiation-induced changes in the absorption spectra of the fluoropolymer films (PTFE, FEP, PFA), can be correlated to the absorbed dose. So, the fluoropolymer films presented excellent dosimetric characteristics and are promising materials as alternatives in high gamma dose quality control (Galante et al., 2010). The study of effects of low dose gamma-irradiation (10–200 kGy) on various fluoropolymers demonstrated that changing in crystallinity degree and tensile strength with radiation dose for PVDF and ETFE is due to competition between crosslinking and chain scission events in polymer structure (Rosenberc et al., 1992). The chemical structure and physical properties of cross-linked PTFE which irradiated by electron beam (EB) (up to 20 MGy) were also studied by Oshima and et al. It has been found that a Y-type crosslinking structure and various types of double bond structures, excluding the crosslinking site, have been formed during EB irradiation (Oshima et al., 2001). The molecular-topological structure of gamma irradiated tetrafluoroethylene-ethylene copolymer, ftorlon polytetrafluoroethylene, polytetrafluoroethylene, viton fluoroelastomers (Ol'khov et al., 2016, 2006, 2014; Olkhov et al., 2013), and the thermo-stimulated luminescence of gamma irradiated polytetrafluoroethylene and tetrafluoroethylene-ethylene copolymer (Nikolskii et al., 2013, 2014) were also previously studied. Investigation of gamma-radiation effect on the molecular-topological structure of polytetrafluoroethylene showed that gamma-irradiation of PTFE could cause remove of intermediate and high-temperature crystalline phases as a result of their transformation into the amorphous phase

* Corresponding author.
E-mail address: h.r.shakur@gmail.com (H.R. Shakur).

https://doi.org/10.1016/j.radphyschem.2017.12.007
Received 8 June 2016; Received in revised form 26 November 2017; Accepted 7 December 2017
Available online 09 December 2017
0969-806X/

(Ol'khov et al., 2006). Study of the morphology of different commercial forms of the tetrafluoroethylene copolymer with hexafluoropropylene (FEP) showed that irradiation effectively reduced the crystallinity of FEPs. In addition, the nature of the radio thermoluminescence and the phase transitions were discussed in detail in this study (Olkhov et al., 2011). Effect of gamma radiation on the molecular-topological structure and properties of poly(vinylidene fluoride) was also studied by Ol'khov and et al. (Ol'khov et al., 2012c). Results showed that five crystalline modifications were arised in the polymer matrix instead of cluster branching points in the initial PVDF. The irradiation eliminated the properties which acquired by the polymer matrix during the fabrication of GRP. The molecular-topological structure of polytetrafluoroethylene has been also studied by a thermo-mechanical spectrometer (Ol'khov et al., 2016). At a dose of 1 Gy, the long-range orientation of chains in the intermediate and high melting crystalline blocks of PTFE were replaced by the short-range orientation of the cluster association structure. Also, found that with increase in absorbed dose, the crystallinity was decreased and the molecular mobility of amorphized chains was enhanced. In addition, both the glass transition and the molecular flow onset temperature of the polymer were reduced.

In the present paper, a detailed study about the effect of gamma radiation with various doses from 0 to 12 kGy on the chemical structure, mechanical and optical properties of polytetrafluoroethylene (PTFE) sheets was reported. The FT-IR spectroscopy was used to study the effect of gamma irradiation on the chemical structure of PTFE sheets and Tensile tests were used to analysis the various mechanical parameters such as necking, Young's modulus, and toughness. Furthermore, effects of gamma irradiation on the different optical properties of Teflon sheets including absorption coefficient, Urbach energy, optical band gaps, refractive index, optical dispersion parameters, and plasma resonance frequency were studied by UV–visible spectroscopy. However, to the best of our knowledge, such a detailed study there has been not reported in any previous work. Considering the importance of Teflon in the various industries such as nuclear and aerospace industry, we believe that the results of this work can greatly help in the process and engineering of the components that use this polymer in their structure.

2. Experimental

2.1. Materials and characterization

An etched PTFE sheet with 260 μm thickness was used to prepare initial samples. The sheet was cut into six strips with dimensions of $2 \times 10\ cm^2$. Five strips were irradiated with different doses of 1, 2, 4, 8, and 12 kGy at ambient conditions, and one strip was used as virgin sample. Irradiator system of gamma cell GC-220 which consist of ^{60}Co rods as gamma source was used for irradiation of samples. The dose rate was 3.65 ± 0.06 Gy/s that measured by Frick dosimeter system according to the ASTM-E1026 standard (ASTM, 2013). Dose distribution inside the irradiation chamber was determined by red perspex-4034 dosimeter system. FTIR spectra were recorded using a spectrophotometer of JASCO (FTIR-6300) with reflection technique (ATR). Also, tensile tests were done according to ASTM-D882 standard (ASTM, 2002) by Zwick universal 1446-60 model, whit 500 mm/min grip separation rate. At last, the absorption and reflectance of UV–visible spectra were recorded by a JASCO (V-670) spectrophotometer using the ATR technique in the wavelength range of 150–900 nm.

3. Results and discussion

3.1. Chemical structural studies

FT-IR spectra of all PTFE samples in the range of 3500–650 cm^{-1} were recorded and shown in Fig. 1. Dominant IR bands at 1200, 1143, 779, 740 and 720 cm^{-1} are belonged to the different modes of $–CF_2–$ groups and band at 650 cm^{-1} are related to –CF deformation. Stretching modes of $–CH_2–$ and $–CH_3$ are appeared in the form of weak IR bands at 2922 and 2852 cm^{-1}. The band at 1460 cm^{-1} corresponded to deformation of $–CH_2–$ and $–CH_3$ groups. The origin of these signals (or impurities) is the surface hydrocarbons that formed on the sheet surface (Fazullin et al., 2015; Mihaly et al., 2006; Nicodom, 2012).

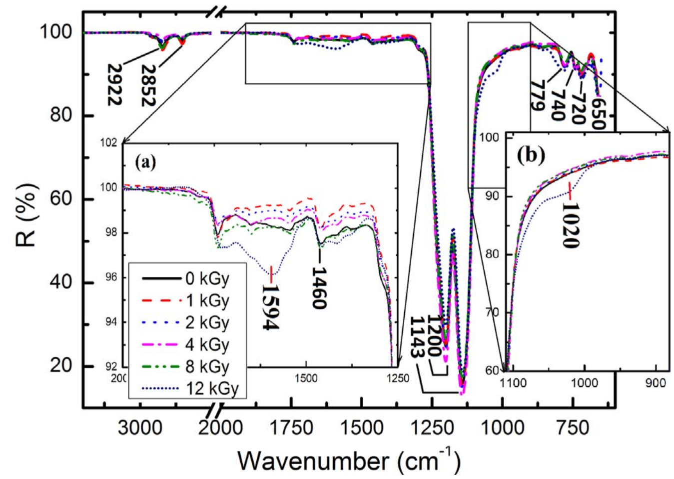

Fig. 1. FT-IR spectra of all samples of Teflon sheets.

Fig. 1a and b compare the infrared spectra of the irradiated and virgin PTFE sheets at different ranges. As it can be seen from these figures, except 12 kGy irradiated sample, there is no important change in FT-IR spectra of irradiated samples compare with FT-IR of the virgin sample. However, in FT-IR spectrum of 12 kGy irradiated sample, there are two important changes compare with the virgin sample. The first one is the formation of 1594 cm^{-1} band that likely belonged to double carbon bonds (Pavia et al., 1995). Formation of double carbon bonds is due to chain scission that occurred in the structure of PTFE. Another important change in the structure of irradiated PTFE sheet is the formation of a band at 1020 cm^{-1} which is relevant to the formation of $–CF_3$ stretching vibration due to the failure of C–C bond (Oshima et al., 2001). The helical structure of individual perfluroalkanes readily distorts due to removal of fluorine. This will have an inappropriate impact on the overall structure of the materials (Allayarov et al., 2007).

Also, the carbon chain of PTFE macromolecules is surrounded by the dense "fluorine coat," which makes the chain inaccessible to many reactive oxidants such as fluorine and oxygen (Ol'khov et al., 2012a).

3.2. Mechanical parameters studies

Tensile test results of all understudy samples are shown in Fig. 2. One can see that in the case of the virgin sample, fracture occurred at the point of UTS (tolerated maximum stress, or ultimate tensile strength) but in the case of the irradiated samples, fracture and maximum stress point occurred at two different points. The strain (Cauchy strain) is defined as the ratio of total deformation to the initial dimension of the material body in which the forces are being applied.

"Necking" is a mode of tensile deformation, where relatively large amounts of strain localize disproportionately in a small region of the specimen. Necking begins at the ultimate tensile strength. Fig. 3a and b illustrate the graph of strain and stress at UTS and at the Fracture strength against the absorbed dose for all understudy samples. Cleary observed that stress at UTS and at fracture were decreased up to 4 and 2 kGy absorbed dose respectively and after that were increased up to 12 kGy, while strain showed a decreasing trend with increasing in absorbed dose at both UTS and fracture points. The degradation of the main chains which was caused by gamma-ray irradiation led to decrease the mechanical strength of irradiated PTFE sheets (Maxwell