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Thermal and mechanical properties of e-beam irradiated butt-fusion joint in high-density polyethylene pipes

Vipin Vijayan, Pashupati Pokharel*, Min Kwan Kang, Sunwoong Choi*

Department of Polymer Science and Engineering, Hannam University, Daejeon 305-811, Republic of Korea

HIGHLIGHTS

- Mechanical property of a butt-fusion joint was improved after e-beam irradiation.
- PE chains at the weld zone were cross-linked by e-beam irradiation.
- The T_c and ΔH_c at the joint were diminished as a function of irradiation dose.
- Raman spectra confirmed the cross-linked structure at the joint after irradiation.

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ABSTRACT

The effects of electron beam irradiation on the thermal and mechanical properties of a butt-fusion joint in high density polyethylene (HDPE) pipes were investigated. Differential scanning calorimetry, X-ray diffraction, and Fourier transform infra-red spectroscopy of welded samples revealed the changes of crystallinity due to the cross linking effect of electron beam irradiation. The suppression of the degree of crystallinity with increasing the irradiation dose from 0 kGy to 500 kGy indicated that the e-beam radiation induced cross-links among the polymer chains at the weld zone. The cross-link junction at the joint of HDPE pipe prevented chain folding and reorganization leading to the formation of imperfect crystallites with smaller size and also less in content. Tensile test of the welded samples with different dose of e-beam irradiation showed the increased values of the yield stress and Young's modulus as a function of irradiation dose. On the other hand, the elongation at break diminished clearly with increasing the irradiation doses.

1. Introduction

Polyethylene (PE) is one of the most commonly used engineering plastic having very durable and extremely tough nature. An excellent combination of stiffness and environmental stress crack resistance of PE made it the leading polymeric material for gas and water pipelines with many desirable properties over metal such as higher chemical and corrosion resistance, lower weight, ease of bonding, and low delivery, construction and maintenance costs. A broad range of piping problems in industrial, municipal, mining, landfill, marine, and agricultural applications have been solved cost effectively by using PE pipe. High-density polyethylene (HDPE) pipes have been used effectively to carry potable water, wastewater, chemicals, hazardous wastes, slurries, and compressed gases. However, the prolonged exposure of all types of PE pipe under the UV rays of the sunlight breaks the molecular chains of PE and generates free radicals, thus the PE pipes lose their flexibility and toughness over a period of time. To overcome such problem, carbon black (CB) based HDPE pipes have been already commercialized having over a minimum lifetime 50–100 years, where CB acts as the best and most economic UV stabilizer after a proper distribution in polyethylene despite storage in the open sunlight (Liu and Horrocks, 2002; Pena et al., 2001). Furthermore, the incorporation of carbon nanomaterials in the polymer not only performs as a UV stabilizer (Wang et al., 2010) but also improves the mechanical properties of polymer composites (Pokharel and Lee, 2014a; Pokharel et al., 2014b; Pokharel et al., 2015c; Pöllänen et al., 2011; Pokharel et al., 2015a; Pokharel et al., 2015b).

High energy electron beam (e-beam) irradiation of polymers and its effects on the chemical structure and physical properties of polymer are in an emergent stage (Zenkiewicz et al., 2008; Dias

* Corresponding authors.
E-mail addresses: ppokharel2008@gmail.com, ppokharel@gm.hannam.ac.kr (P. Pokharel), swchoi@hnu.ac.kr (S. Choi).

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and Silva, 2007; Czaja and Sudoł, 2011). The e-beam irradiation of polyethylene results in main-chain scission, cross-linking and evolution of hydrogen gas. The nature of irradiation as well as the chemical and physical state of polymers determines the final properties of the irradiated materials (Zaydouri and Grivet, 2009; Murray et al., 2012). The e-beam irradiation was already employed for cross-linking PE chains for the production of heat shrinkable polyethylene films and tubes in the industry. The cross-linked polyethylene is also used in wire and cable industries as well as the hot water piping installation system. The deep penetration capacity of a 10 MeV electron beam is very important to crosslink the thick-walled HDPE pipe. Khonakdar et al. (2006) reported the effect of e-beam irradiation on cross-link density and crystalline structure of low- and high-density polyethylene. In their study, the crystallization behavior was restricted after a series of cooling and heating the irradiated samples due to decrease the length of chain segment needed for usual crystallization by chain folding through the formation of cross-link joints. Murray et al. (2012) also reported similar effect of high energy e-beam irradiation on the thermal and structural properties of low density polyethylene (LDPE).

Welding technology is very important in production, repair, and recycling of plastic materials in which the major target is to develop the strongest joint after the welding (Leskovics et al., 2006; Lee et al., 2012; Wool et al., 1989; Schmachtenberg and Tuchert, 2003; Barber and Atkinson, 1972; Lee and Epstein, 1982). The optimization of the quality of the weldment and the generation of the original properties of raw materials after repaired are the key issues in the welding technology. Schmachtenberg and Tuchert (2003) showed the effect of the microstructure of welded area of polypropylene in which long-term tests were found suitable for examining the different weld seam qualities. Leskovics et al. (2006) examined the structure and the mechanical properties of a butt weld in a polyethylene pipe and contrasted to non-welded PE pipe. From tensile and notched impact tests at ambient and sub-ambient temperatures and varying rates of impact, they confirmed the reduced resistance to failure of welded PE consistently. Simple tensile test has been already employed to determine the optimum conditions of butt fusion welded polypropylene pipes (Barber and Atkinson, 1972) in which the removal of the welding beads confers a clearer picture to achieve the welding performance. Even though there are various factors that affect the strength and the quality of the weld zone of the PE pipe (Balkan et al., 2008; Bowman and Parmar, 1989; Pimputkar 1989; Ageorges et al., 2001; Barber and Atkinson, 1974; Krishnaswamy and Lamborn, 2005; Nie et al., 2011; Lu et al., 2002), we believe that the cross-linking of the PE molecules at the weld zone of the PE pipe can enhance the mechanical properties of weld seam. In this circumstance, even the conventional short-term test like tensile test after the removal of the welding beads can give information about the quality of the weld seam. In this study, HDPE pipes were welded by butt-fusion technique at 231 °C. Then, each welded pipe was cut into 6 pieces and irradiated with a high energy e-beam at dose range of 100, 250, and 500 kGy. The mechanical and thermal properties of the welded HDPE pipe in the different doses of 10 MeV electron beam were compared with each other and also with the non-irradiated pipe.

2. Experimental

2.1. Materials

The pipe material is a high density polyethylene (HDPE) made by COSMO, Korea under a trade name KSM 3408-2. The extruded pipe of 110 mm diameter and wall thickness 10.1 mm was used in

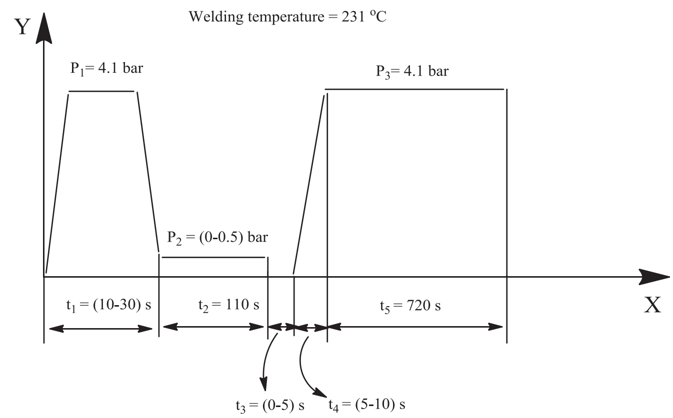

Fig. 1. Schematic showing the butt fusion welding of HDPE pipes.

this study. The HDPE pipe contains ~2 wt% carbon black as a UV stabilizer. The each welded pipe was cut into 6 pieces with the weld zone at the center before e-beam irradiation. All the samples were irradiated without removing the bead and cut transversely into 50 μm thin slice using microtome (ERMA INC, ESM-150S, Japan) for the characterization by DSC, Raman, and FT-IR. Thickness of sample ~1 mm was used to measure the wide angle X-ray diffraction patterns. The dogbone-shaped specimens were made by milling for the tensile test.

2.2. Butt-fusion welding of HDPE pipes

The butt-fusion welding of HDPE pipes was performed at 231 °C under 0.41 MPa compression pressure by using automatic butt fusion machine (NUC-II WMS, world map system, Korea). Fig. 1 shows a plot of pressure versus time during the butt fusion welding of HDPE pipe at 231 °C. The exact value of time (t) and pressure (p) during the initial bead up (t_1,p_1), heat soak (t_2,p_2), heat plate removal (t_3), fusion jointing (t_4,p_3) and cooling-cycle (t_5) are clearly shown in the figure of welding profile. Fig. 2 shows (a) HDPE pipe with a butt-fusion weld, (b) sample for e-beam irradiation, (c) rectangular bar shaped sample after milling, (d) dogbone-shaped specimens, and (e) HDPE weld obtained after microtome. The sample for DSC and XRD were taken from white rectangle as shown in Fig. 2(e). Similarly, an FT-IR in ATR mode was measured at the circles and Raman spectra were measured at the center of the middle circle.

2.3. Electron beam irradiation of butt-welded HDPE pipes

All the samples were irradiated at room temperature in presence of air at the EB-TECH, Daejeon, South Korea. The UELV-10-10S model with linear electron accelerator of 10 MeV was used to irradiate the samples at the doses of 100, 250, and 500 kGy. Here, the non-irradiated samples provided as the baseline for each of the results acquired from the characterization techniques. The information about the e-beam irradiation of welded HDPE pipes is shown detail in Table 1.

2.4. Characterization

A differential scanning calorimetry (TA Instrument DSC2920) was used to measure the DSC thermograms of the non-irradiated and e-beam irradiated welded zone of HDPE pipes. The weight range of the samples was taken between 2–3 mg from the specified welded portion of the sample for DSC measurement. All samples were ramped from 25 to 200 °C at a rate of 10 °C/min under pure nitrogen and then cooled down to 25 °C at the same