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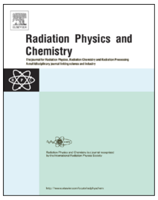

Evaluation of fatigue crack behavior in electron beam irradiated polyethylene pipes

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HIGHLIGHTS

- Effect of e-beam irradiation on SCG behavior of PE was evaluated using a CRB test.
- High degree of cross-linking could endure low dynamic load effectively.
- CRB method confirmed brittle fracture surfaces as an indication of a SCG failure.
- The slope of fatigue failure curve was increased at high dose of irradiation.

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ABSTRACT

A cracked round bar (CRB) fatigue test was employed to determine the slow crack growth (SCG) behavior of samples from high density polyethylene (HDPE) pipes using PE4710 resin. The structure property relationships of fatigue failure of polyethylene CRB specimens which have undergone various degree of electron beam (EB) irradiation were investigated by observing fatigue failure strength and the corresponding fracture surface morphology. Tensile test of these HDPE specimens showed improvements in modulus and yield strength while the failure strain decreased with increasing EB irradiation. The CRB fatigue test of HDPE pipe showed remarkable effect of EB irradiation on number of cycles to failure. The slopes of the stress-cycles to failure curve were similar for 0–100 kGy; however, significantly higher slope was observed for 500 kGy EB irradiated pipe. Also, the cycle to fatigue failure was seen to decrease as with EB irradiation in the high stress range, $\Delta\sigma = (16\text{ MPa to }10.8\text{ MPa})$; however, 500 kGy EB irradiated samples showed longer cycles to failure than the un-irradiated specimens at the stress range below 9.9 MPa and the corresponding initial stress intensity factor $(\Delta K_{I,0}) = 0.712\text{ MPa m}^{1/2}$. The fracture surface morphology indicated that the cross-linked network in 500 kGy EB irradiated PE pipe can endure low dynamic load more effectively than the parent pipe.

1. Introduction

Radiation induced crosslinking of polymers has been found very useful for chemical processing applications in different industrial areas (Clough, 2001). When the radiation passes through the material, it produces very reactive intermediates, free radicals, ions and excited molecules (Bhattacharya, 2000). Even though the modification and enhancement of polymeric materials are possible through the utilization of electron beam (EB), the irradiation techniques are not fully utilized over the past few decades. Chmielewski et al. (2005) presented a survey of radiation processing methods of industrial interest and adjacent technologies which are already well established with distinct promises for future commercial use. EB irradiation can alter the thermo-mechanical characteristics of cross-linkable plastics such as dimensional stability, stress cracking resistance, service temperature, and solvent and water permeability.

Mechanical properties of the polymer composites are improved with the incorporation of carbon nanomaterials in the polymer matrix (Pokharel and Lee, 2014a; Pokharel et al., 2015b, 2015d). Even though thermal, electrical, and mechanical properties of composites could improve with the addition of nanofillers, there might be chances of residual solvents and additives that were used for the fine dispersion of nanomaterials in the polymer matrix (Pokharel and Lee, 2014b; Pokharel et al., 2015a, 2015c). Radiation cross-linking is a pure physical process which is technically and economically feasible; and there are no residues of additives formed like in the chemical processes (Vijayan et al., 2016). In the EB radiation technique, absorption of energy by the backbone

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polymer initiates a free radical process. Interestingly, EB radiation techniques have the capability of initiation in solid substrates as well as the better regulation of the molecular weights of the products with slightly increasing the temperature even at high dose of irradiation. Additionally, EB irradiation techniques have been frequently used for the cross-linking of the polyethylene chains (Bhattacharya, 2000; Chmielewski et al., 2005). A large volume of literatures about ultrahigh molecular weight polyethylene (UHMWPE) exists on the topic related to the impact of cross-linking on wear resistance, fatigue life, and fatigue crack propagation rate (Urriés et al., 2004; Puértolas et al., 2006; Visco et al., 2009). Puértolas et al. (2006) analyzed fatigue behavior of a highly cross-linked UHMWPE after EB irradiated as well as subsequently re-melted at 150 °C. In their study, the stress-life curves showed loss of fatigue strength when the final re-melting process was applied after irradiation due to the loss of crystallinity content after re-melting as well as decreased the defect initiation resistance. Although the irradiation positively contributed to total life analysis, the fatigue resistance of notched components found negative effect on the both processes. Visco et al. (2009) reported the effect of EB irradiation on UHMWPE samples in air and in vacuum under different thermal conditions in which they observed good mechanical performance and wear resistance on the 100 kGy irradiated UHMWPE under vacuum at 110 °C and annealed at the same temperature for 1 h.

Polyethylene pipes have been using effectively for the transportation of gas or water from many decades ago. Considerable experience regarding to the failure behavior as well as the conditions for the propose of PE piping systems is available. An ISO 9080 classifies the materials based on the internal pipe pressure tests to ensure sufficient lifetimes of pressurized pipes (Frank and Pinter, 2014). Such tests provide the information about the minimum required strength (MRS) to ensure pipe lifetimes of at least 50 years. The ASTM F2788M covers the standard specification for metric and inch-sized crosslinked PE pipe including the test methods for hydrostatic sustained pressure, excessive temperature-pressure, environmental stress cracking, oxidative stability in potable chlorinated water, degree of crosslinking, etc. Since cross-linked PE is very much resistant to slow crack growth, not much work has been reported. Nowadays PE4710 and PE 100-RC (RC=Resistant to Crack) with improved resistance to slow crack growth (SCG) generated new challenges for material characterization on the economic and practical perspectives. For the characterization of the SCG resistance of modern PE pipe grades, several new test methods have been developed (Frank et al., 2009; Frank and Pinter, 2014; Guedes, 2011; Kolařík and Pegoretti, 2008; Kratochvilla et al., 2014; Nitta and Maeda, 2010; Pinter et al., 2007; Pyo et al., 2010). Generally, different parameters such as higher temperatures, higher test stresses, higher test velocities and special environments (wetting agents) have been used to accelerate SCG behavior (Fleissner, 1998; Hiroyuki and Ikuo, 1991; Lu et al., 1997). Still, there are limitations of these conditions to get brittle fracture surfaces for characterizing SCG. On the basis of linear elastic fracture mechanics (LEFM), Notched Pipe Test (NPT), Full Notch Creep Test (FNCT) or Pennsylvania Edge Notch Tensile (PENT) test proved the applicability to polymeric materials within specified boundaries. From these studies, the failure mechanisms under static loading conditions are understood and try resembling the cyclic loads. So, the application of fatigue test also becomes an alternative for accelerated material characterization (Djebli et al., 2014; Haager et al., 2006; Hiroyuki and Ikuo, 1991; Pinter et al., 2007; Urriés et al., 2004; Zhao et al., 2013). Kratochvilla et al. (2014) employed the cracked round bar test (CRB) to determine the long term slow crack growth behavior of PE pipes and the results were compared to two notch creep test (2NCT), accelerated notch pipe test (ANPT) and Charpy impact test. They found a linear correlation between all these standardized test methods for PE pipes with the CRB test. Similarly, Frank and Pinter (2014) evaluated the applicability of the cracked round bar test as standardized PE-pipe ranking tool at ambient temperature even for modern PE100-RC.

Outstanding CCG resistance of the third-generation PE resins has obtained by the specific improvements in the polymerization process through a bimodal distribution of the molecular mass and the specific placement of the short-chain branches on the high molecular mass fraction (Deblieck et al., 2011). To evaluate the long-term behavior of modern PE pipe materials, quicker test methods in practicable time frames are essential. For the high-performance PEs, CRB test is an appropriate method to propagate cracks by purely mechanical means to characterize the fatigue crack growth (FCG) behavior. We believe that resistance against SCG is important for the lifetime of PE pipes and the FCG experiments are faster when characterizing modern (bimodal) PE. EB irradiation increases the degree of cross-linking of PE chains and that can control by a suitable choice of the electron energy, by multiple irradiations with different electron energies or reduce their energy before they reach the product surface as a result locally different material properties can generated from one parent material. For cross-linked bimodal PE pipe, CRB test are effective to obtain SCG results within few days. There are not any studies about the effect of EB irradiation on the evaluation of SCG behavior in new grade PE pipes. One of the major goals of the present article is to investigate the effect of high dose of EB irradiation on fatigue resistance as well as other mechanical and physical properties of PE pipes. In this study, 30 mm thick rectangular bar was irradiated under 10 MeV electron beam for 100 and 500 KGy dose and milled into round bar having diameter 25 mm for CRB test.

2. Experimental

2.1. Materials

The large diameter HDPE pipe from PE4710 resin (melt index=0.25 g/10 min at 190 °C/5.0 kg, density=0.959 g/cm^3, σ_y =25 MPa) manufactured by COSMO Korea was used for this experiment. The extruded SDR9 pipe having 450 mm diameter and wall thickness 50 mm was cut into 15 pieces, and milled into rectangular bars having dimension ($30 \times 30 \times 140$ mm^3) before EB irradiation. The dogbone-shaped specimens of the un-irradiated and EB irradiated samples were made by milling around the center of pipe for the tensile test.

2.2. Electron beam irradiation of HDPE pipes

For the cross-linking of PE chains, rectangular bars (thickness=30 mm) made from the large diameter HDPE pipe were irradiated under the high energy electron beam. The UELV-10–10S model with linear electron accelerator of 10 MeV was used to irradiate the samples at the doses of 100 and 500 kGy at room temperature in presence of air at EB-TECH, Daejeon, South Korea. During irradiation, the direct exposed side of the samples was turned up and down into several steps to get the homogeneous effect of irradiation. Here, the non-irradiated samples offer as the baseline for each of the results obtained from the characterization techniques. The detail information about the EB irradiation of HDPE pipes is given in our previous study (Vijayan et al., 2016). The mechanical tests of the EB irradiated samples were performed after storing at 25 °C for a week.