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The effect of high-energy electron beam on drawn and undrawn high density polyethylene fibers

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ABSTRACT

HDPE monofilaments were obtained using different extruders and drawn by post-extruder equipments. After solidification, drawn and undrawn monofilaments (draw ratio 7:1) were irradiated with 10 MeV electron beams in air at room temperature at 25, 50, 75, 100 and 125 kGy doses to induce a network structure. The phenomenon of the HDPE crosslinking was studied on the basis of gel content measurements. The fibers were examined by differential scanning calorimetry (DSC) and mechanical properties measurements. It was noted that the gel fraction increased with the irradiation dose up to 75 kGy and showed a significant increase with draw ratio, but at higher doses remained without considerable change. Melting temperature of drawn fiber increased with raising irradiation dose but decreased in undrawn sample. Also a bimodal endotherm peak was observed for drawn polyethylene irradiated in air. The changes in melting temperature and appearance of bimodal endotherm were related to the radiation chemistry of polyethylene in the presence of oxygen and interlamellar interactions. Heat of fusion and degree of crystallinity slightly increased for undrawn and drawn samples but, heat of crystallization was reduced by increasing irradiation dose due to the increase in the degree of crosslinking. The results of mechanical properties revealed that no significant changes occurred in Young's modulus by increasing irradiation dose. As a result of oxidative degradation happened by the presence of the oxygen molecules during the irradiation process, the tensile properties of irradiated fibers decreased but elongation-at-yield for undrawn and elongation-at-break for drawn fibers boosted by increasing irradiation dose up to 125 kGy. **Polyolefins J (2015) 2: 109-119**

Keywords: polyethylene fiber; electron beam; crosslinking; draw ratio

INTRODUCTION

In view of the potential applications of high modulus polyethylene fiber in ropes, high performance materials, self-reinforcement composites and other situations where load-bearing capability is important, considerable attention has been given to the study of mechanical behavior [1]. It was recognized that crosslinking by irradiation could be potential value in reducing permanent flow and improving the strength and stiffness of these fibers either before or after drawing. Also it was reported that irradiation of drawn fibers of polyethylene could produce very dramatic improvements in creep behavior [2-3]. Crosslinking can be accomplished either by high energy irradiation or through using chemical crosslinking additives [4-6]. A rapid and popular technique of crosslinking in polymers is high energy radiation. The physical, chemical and utility properties of polymer materials can be altered by high energy

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radiation. The first investigations of radical reactions after gamma-irradiation in polymers were published in the early 1950s [7-8]. Polymers irradiation provides free radicals formation. Reaction of these free radicals together can result in crosslinking and chain scission [9-11]. Crosslinks, main chain scission (degradation) and hydrogen gas evolution are the permanent effects of high energy radiation on polyethylene. These reactions are related to the chemical and physical state of the polymer and the nature of irradiation [12- 15].

The ratio of main chain scission to crosslinking determines whether gel will be produced. If the ratio of scissions to crosslinks caused by irradiation is larger than 4, no gel will be formed [16].

In case of vinyl polymers, there is a correlation of irradiation effect with chemical structure that permits these polymers to be classified as whether they crosslink or degrade when irradiated [13].

Polyethylene mainly crosslinks because of its structure. Crosslinks are mostly generated in the amorphous region and at the crystal fold surfaces. It should be mentioned that no crosslinking occurs within the crystal lattice [17-18].

One of the effective parameters that influences irradiation efficiency is irradiation atmosphere [19-20]. In the case of PE, crosslinking is the predominant effect upon irradiation occurred in the absence of oxygen. But, if irradiation takes place in the presence of oxygen or air, oxidative degradation will become a major process [21-25]. Consequently, the molecular weight decreases via radiation dose [26].

It should be mentioned that radiation dose rate and dimension of irradiated sample have influence on oxygen side effects. It is also reported if PE irradiates with high dose rates at the presence of air, it will show similar behavior to the kind of PE which is irradiated in vacuum [12, 27].

Seguchi also reported that the irradiation of polyethylene by Cobalt 60-gamma ray in the presence of oxygen at ambient temperature showed a larger decrease in elongation and tensile strength than those in the polyethylene sample which was irradiated under the vacuum condition [23]. Investigation on the highly drawn polyethylene fibers demonstrated that degree of crosslinking in acetylene was much higher than that in vacuum in the equivalent dose [28].

Investigation on the thermal properties of the crosslinked PE irradiated with electron irradiation at the presence of air in room temperature has shown that the melting point (T_m), heat of fusion (ΔH) and crystallinity were not significantly changed by increasing irradiation doses but the temperature of crystallization (T_c) was reduced [4].

Gheysari also reported that using high energy electron beam irradiation in air at room temperature, the T_m and T_c of HDPE decreased as a function of irradiation dose [14].

Crystallization methods, thermal measurement techniques and irradiation conditions such as temperature and irradiation atmosphere play a pivotal role in the evaluation of the thermal properties of the polyethylene irradiated by electron beam and the results assessment is strongly dependent on them. Therefore, different results have been reported.

Zoepfl [18] illustrated that changes in the first melting temperature caused by irradiation was related to the melt entropy and fold surface free energy per unit area of chain folded PE crystals.

An increase in electron beam irradiation temperature results in an increases in the PE crosslinking efficiency [29-30]. Gheysari [31] also reported boosting the energy of electron beam irradiation from 5 to 10 Mev in air at room temperature, caused increasing chain scissions and reduced crosslinking efficiency at the same doses. Perkins and coworkers [15] reported that irradiating ultra oriented polyethylene fibers with gamma radiation under vacuum, increased tensile strength and elongation-at-break up to 200 kGy. Induced crosslinking, which leads to an enhancement in the molecular weight, was the main factor, they proposed. Ward and coworkers [1] investigated the drawing behavior of linear polyethylene monofilaments which were irradiated under vacuum. According to the results, the relation between the tensile strength and irradiation process was mostly dependent on the drawn polymer morphology, they proposed. They mentioned that the irradiation process before drawing operation approximately had no effect on the changing of tensile strength. They also reported that strain at failure depended on the molecular network affected by crosslinks.

Some researchers also remarked that appropriate

draw ratio could have considerable effect on the properties of irradiated samples [28, 32-33].

In this work, undrawn and drawn HDPE monofilaments with approximately 7:1 draw ratio were produced and irradiated with high energy electron beams with 10 MeV in dose range of 25, 50, 75, 100 and 125 kGy in air at 25°C. The effect of irradiation on gel content (undissolved fraction), thermal properties including melting temperature, heat of fusion, heat of crystallization and mechanical properties have been studied. Effect of draw ratio on crosslinking efficiency has also been investigated.

EXPERIMENTAL

Materials and sample preparation

Two types of HDPE, namely, BL3 and HB0035 were used for studying their radiation properties. Table 1 shows their specifications. Melt flow index was determined according to ISO 1133 with Xnr-400a (made in China).

Fibers were prepared by melt spinning process. Three single screw extruders with different conditions were used for fiber spinning. Table 2 illustrates single screw extruder specifications.

PE was extruded through a spinneret with several holes. While the polymer passed the air gap (10-15cm) and fiber structure was formed, monofilaments were entered into a water bath at 25°C to prevent them not to stick together. Then, monofilaments were entered into a hot water bath (85°C) for preparing solid-stated drawing. After passing the dryer, the solid filaments were stretched on cold drawn process. The draw ratio for all samples was approximately 7:1. Figure 1 shows a sketch of the fiber spinning and solid-state drawing line.

The drawn and undrawn fibers used for irradiation test are shown in Table 3. Bl3 and HB0035 were mixed with 3:1 ratio and named "blend" for investigating the effect of the molecular weight distribution on the irradiated monofilaments.

Table 1. HDPE grades used for fiber spinning and irradiation properties.

HDPE	Petrochemical Co	MFI 190°C (g/10min)	Density (g/m³)
HB0035	Bandar Imam	0.444(2.16kg)	0.959
BL3	Jam	0.283(2.16kg)	0.954

Table 2. Specifications of single screw extruders used for fiber spinning.

Group	Extruder type*	L/D	N (rpm)	cylinder temperature (°C)						Draw ratio (λ)
				1	2	3	4	5	6	
I	PROTON 90	24	70	230	240	262	259	258	232	6.82
II	PROTON 90	26.5	74	212	225	231	229	228	-	6.28
III	PROTON 60	30	70	190	210	215	225	235	-	6.9

* CINCINNATI single Screw

Samples Irradiation

The irradiation was carried out at Yazd Radiation Processing Center using an electron beam accelerator RHHDOTRON TT200. The specifications of the electron beam accelerator are given in Table 4. For investigating the effects of high energy electron beam on HDPE fibers, samples were irradiated with 10Mev and 3mA electron beam in the air at room temperature by irradiation doses of 25, 50, 75, 100 and 125 kGy.

Gel Measurements

The gel content of crosslinked HDPE was determined according to ASTM D 2765 using 12 h Soxhelet extraction cycle with p-xylene as the solvent at 140 °C. Irganox 1010 was added at 0.01 wt% to inhibit polymer degradation during the extraction. The gel fraction was calculated as a percentage ratio of the final weight of the polymer to its initial weight.

Thermal analysis

The differential scanning calorimetery (DSC) test was performed on a DSC 200F 3 M of NETZSCH (Ger-

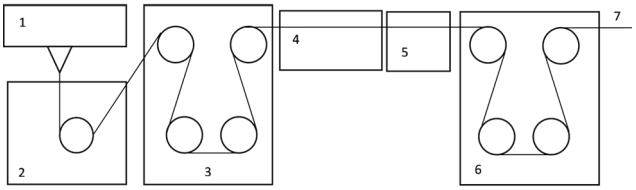

Figure 1. sketch of the fiber spinning and solid-state drawing line: (1: extruder + nozzle, 2: water bath 25°C, 3: primary drawing, 4: hot water bath 85°C, 5: dryer, 6: cold drawing, 7: winding).

Table 3. Drawn and undrawn PE fibers used for irradiation test.

No	Group	Polymer Grade	Status	Tex
S1	I	Blend	Undrawn	492
S2	I	Blend	Drawn	97
S3	II	HB0035	Undrawn	533
S4	III	HB0035	Drawn	95
S5	III	HB0035	Undrawn	575
S6	III	Bl3	Drawn	77
S7	III	Bl3	Undrawn	421

many) in a temperature range between +25 and 350°C at a heating rate of 10°C/min. Melting temperature and crystallization enthalpies for the irradiated fibers were measured. The degree of crystallinity was calculated via the total enthalpy method according to the following equation:

$$X_c = \frac{\Delta H_m}{\Delta H_{m,100}} \quad (1)$$

Where X_c is the degree of crystallinity, ΔH_m is the specific enthalpy of melting and $\Delta H_{m,100}$ is the specific melting enthalpy for 100% crtystalline PE. The value of 288 J/gr was used for $\Delta H_{m,100}$ [4].

Mechanical Measurements

Mechanical properties of fibers were determined with tensile machine, Hiwa 200, with 7 cm gauge length and 200 mm/min extension rate. Tensile strength (TS) and elongation-at-break (EB) for the drawn irradiated samples and tensile yield stress (TY) and elongation-at-yield (EY) for the undrawn irradiated samples were determined. Young modulus for all fibers was determined at 1 percent strain.

RESULTS AND DISCUSSIONS

Gel Content

Figure 2 shows the variation of gel content as a function of irradiation dose for undrawn fibers. It is observed that gel content increases rapidly by raising irradiation dose and reaches up to 50% at 100 kGy for all samples. The results indicate that the irradiation doses between 75 to 100 kGy are sufficient to make the polymer insoluble and it can be concluded that applying dose rates higher than 100kGy has no effect on polymer insolubility or, indeed the gel content.

Table 4. RHODOTRON TT200 electron beam accelerator parameters.

Beam Energy	10 MeV
Beam Power at 10 MeV	≧70 kW
Energy dispersion at 10 MeV	±300 keV
Scanning range	30-100 cm
Total power consumption	<300 kW
RF	107.5 MHz
RF power output	200 kW
Electron gun average current	0-10 mA
Resolution	±50 μA

As mentioned above, crosslinks are mostly generated in the amorphous region. So, the higher value of the gel content represents the higher degree of crosslinking in the amorphous region.

Because chain scission is the dominant operation in the irradiated polymer with high doses, gel content decreases by escalating of irradiation dose up to 125 kGy. It has been reported that if polyethylene is irradiated in the presence of oxygen at room temperature, free radicals will react with oxygen present in the atmosphere and cause chain degradation process [1].

The PE grades, BL3 and HB0035 , have different MFIs and different average molecular weights. Hence their blend has a wider molecular weight distribution. In Figure 2 it is seen that the rate of increase of gel content as a function of irradiation dose is smaller for the blend sample (S1). Crosslinking and chain scission occur simultaneously in the PE under radiation. However, the longer polymer chains are more susceptible to crosslinking . The S-shape curve of the gel content of the blend implies that in low doses (below

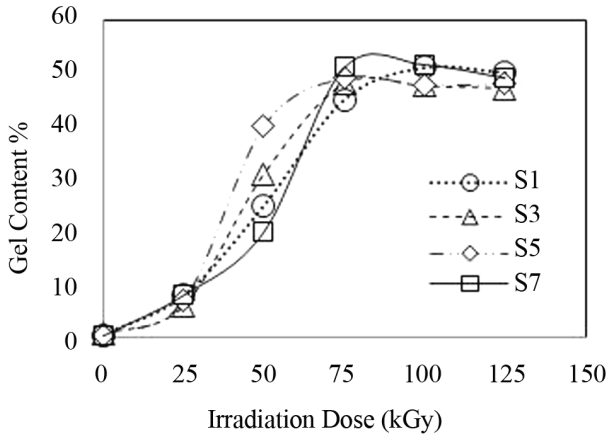

Figure 2. Variation of the gel content as a function of irradiation dose for undrawn HDPE fibers.

75 kGy) the effect of intact low MW chains making the sol content is dominant over that the gel making high MW chains.

Drawing process changes the gel content by means of the amount of chain orientation, crystallite size and degree of crystallinity. Accordingly, the gel content of one selected drawn monofilament was also measured. Figure 3 shows the plot of gel content versus irradiation dose for the BL3 monofilament. As can be seen, the crosslinking efficiency in the drawn monofilaments is greater than that in the undrawn sample.

Since crosslinks are recognized to be confined to the amorphous phase or at the crystal fold surfaces, it can be concluded that the sample with lower crystallinity (undrawn sample) has higher gel content but, an unexpected behavior is observed in Figure 3. To explain this unexpected treatment, it should be stated that the most effective crosslinks ,which cause to form a gel with higher gel content, are those specific linkages which link adjacent lamellae to each other [28]. Those crosslinks which are formed between lamellae are effective and provide polymer insolubility or gel content while those that are formed intra-lamellarly are ineffective [34].

In drawing process, the initially isotropic lamlellar structure is transformed into a fibrous structure composed of bundles of thin microfibrils with higher interlamellar interactions than undrawn sample [32]. Accordingly, when there is a good interlamellar contact, we will have higher gel fraction and this would tend to be the case for the fiber with a high draw ratio.

It must be mentioned that transforming isotropic lamlellar into a fibrous structure completed at draw ratio of 9-10:1[28,32] and at the higher draw ratio in which the crystallinity is high, leads to fewer sites being available for corsslinking. Therefore the effect of chain scission is more obvious.

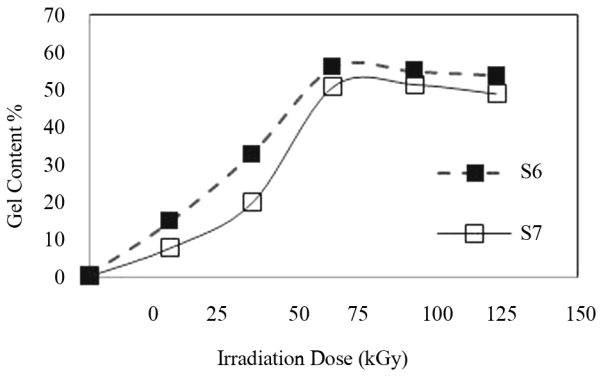

Figure 3. Plot of gel content versus irradiation dose for drawn and undrawn HDPE monofilament.

Charlesby-Pinner Plots

In order to quantify the effect of orientation on irradiation crosslinking efficiency, we used the Charlesby-Pinner equation:

$$s+\sqrt{s}=\frac{\lambda}{2}+\left(2-\frac{\lambda}{2}\right)\frac{D_g}{D} \quad (2)$$

Where s is the sol fraction, D is the radiation dose (Mrad), $\lambda=\frac{G(s)}{G(X)}$ (where G(X) is the yield of crosslinks per 100 eV of irradiation energy absorbed and G(s) is the yield of chain scission for the same amount of energy absorbed) and gelling dose, D_g, is the radiation dose required to reach the gel point. The ratio of chain scission to crosslinking, λ, can be estimated from the maximum gel fraction, g_{max}, at infinite dose by using the Inokuti equation[32].

$$g_{max}=\frac{1}{2}(1-\lambda+(1+2\lambda)^{1/2}) \quad (3)$$

The results of g_{max}, λ and D_g for all samples are listed in Table 5. By considering the Charlesby-Pinner equation, it is necessary to have gelling dose for the irradiated samples. The gel content calculated for four undrawn and one drawn samples is illustrated in Figures 2 and 3. So, all these data used for this equation and the results have depicted in Figure 4.

According to the equation the value of $s+\sqrt{s}$ varies between 0-2. If there is no chain scission G(s)=0, then λ=0 and $s+\sqrt{s}$ tends to 0. When λ=4 (ratio of chain scission to crosslinking), $s+\sqrt{s}$ tends to maximum. At this state, as it was mentioned before, no gel will be formed. Thus, when $s+\sqrt{s}$ approaches to lower values, we will have higher crosslinking efficiency. As

Table 5.Values of gmax , l and Dg for undrawn and drawn samples.

sample	g_{max}	L	$D_g^{(MRad)}$
S1	0.51	2.380000000	1.88
S3	0.48	2.482220510	1.736
S5	0.49	2.448285686	1.455
S6	0.56	2.206649916	1.34
S7	0.515	2.362838828	1.95

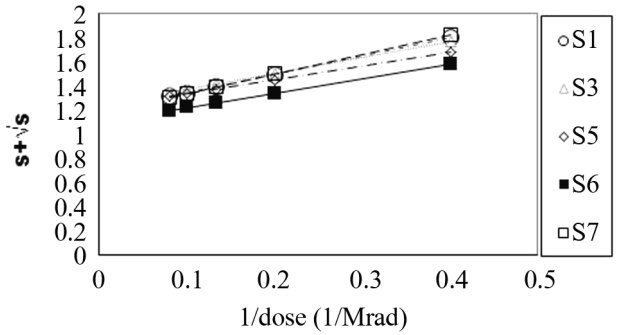

Figure 4. The Charlesby-Pinner plots for undrawn and drawn HDPE monofilaments.

Figure 4 illustrates, $s+\sqrt{s}$ tends to lower values when irradiation dose increases and molecular orientation also accelerates this phenomenon.

Thermal Properties

Changing of melting temperature (T_m) versus irradiation dose for the undrawn fiber is illustrated in Figure 5. As can be seen T_m decrease gradually by raising the irradiation dose. The Tm sensitivity to irradiation dose is related to fiber morphology, location of the crsosslinks and the extent of chain scission [28].

As a result of irradiation process, radicals are being formed in the crystalline, amorphous and interfacial regions. By considering the high mobility of polymer chains in amorphous region, the radicals react together rapidly. However, due to the hindered mobility of the chains in crystalline region, the radicals are frozen in. Thus, no crosslinking occurs in the crystalline region.

During the melting process in the first heating cycle, the chain's mobility increases and frozen radicals are mobilized. Now they are able to crosslink on the crystalline region. These crosslinks amplify defects in the chain structure and cause slight changes in the melting temperature. In addition, during the irradiation process in the presence of oxygen, the radicals can react with dissolved oxygen molecules in the amorphous and interfacial regions and form peroxy radicals. These peroxy radicals are the main culprit of decreasing T_m by means of chain scission process. Similar results have been reported by Zoepfl [35].

Figure 6 shows the plot of melting temperature (T_m) versus irradiation dose for selected drawn and undrawn samples. As can be seen, Tm increases for drawn monofilaments. According to the previous statements, the radiation induces the crosslinks in the amorphous regions and at the crystal fold surfaces.

Crosslinking in the amorphous phase decreases the melt entropy which increases the T_m. On the contrary, the crosslinks at the crystal fold surfaces raise the free energy and decrease the T_m [18]. It was also reported that crosslinking in the amorphous phase results in a depression of the T_m by virtue of increasing the entropy of fusion [28]. Scissions produced by reactions of peroxy radicals in the interfacial regions would be expected to increase the melt entropy and results in decrease in T_m [35].

So, links at the fold surfaces induce two competing effects: they tend to raise the first melting temperature by decreasing the melt entropy and reduce the first melting temperature by increasing the fold-surface free energy. Chain scission in the crystal or amorphous phase also decreases T_m.

The increase in T_m with draw ratio can be understood simply in terms of increasing the lamella thickness and more inter-lamellar interactions. In drawn samples, links, which are intermolecular, decrease

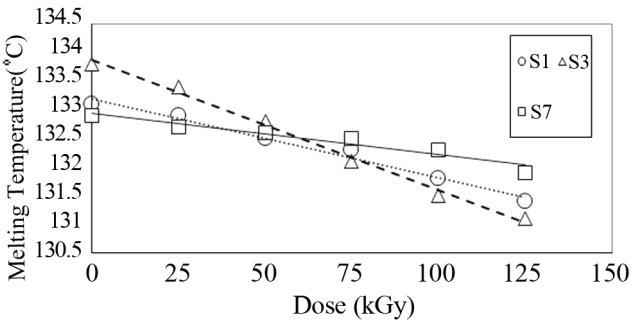

Figure 5. Changes of melting temperatures as a function of irradiation dose for undrawn HDPE fibers.

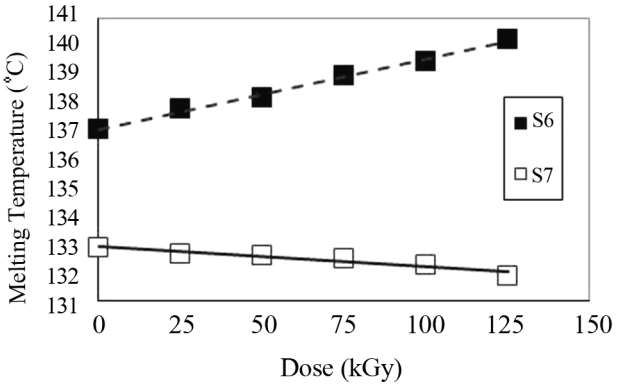

Figure 6. Changes of melting temperature as a function of irradiation dose for drawn and undrawn HDPE fibers.

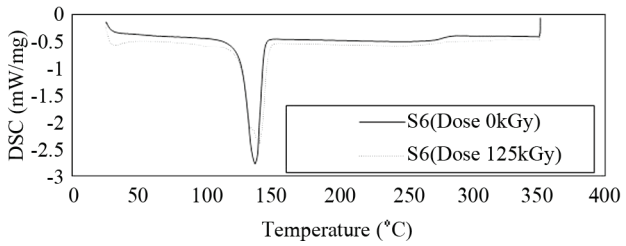

Figure 7. DSC thermograms for the crosslinked and uncrosslinked drawn HDPE fibers.

the melt entropy. In undrawn sample, links, which are more intramoleculare, take place on the fold-surface and increase the fold-surface free energy which results in a depression of T_m. Similar results have been reported by Zoepfl and klein [18, 28]. At higher draw ratio, the friction of amorphous phase will be less, hence, producing higher probability for chain scission and crosslinking at the fold surfaces results in decreasing in T_m.

Figures7 and 8 show the DSC graphs for selected drawn and undrawn samples, respectively. As seen in Figure 7, the fusion endotherm for the drawn monofilaments becomes bimodal when they are irradiated in the presence of air, while this behavior is not observed for the undrawn sample (Figure 8).

Zoepfl [35] has reported that the most effective parameters which cause formation of bimodal endotherms for HDPE irradiated in the presence of air are: scissions produced by the reaction of oxygen with radicals at the chain folds and reorganization (lamellar thickening). The higher peak value is attributed to a fibrillar structure consisting, extended chain crystals which are produced by drawing process and the lower melting peak may result from a less oriented crystalline component [36].

Figure 9 shows an increase in the enthalpy of fusion (ΔH_m with irradiation dose. Changes in the degree of

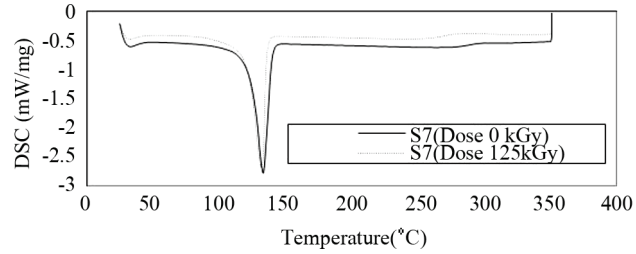

Figure 8. DSC thermograms for the crosslinked and uncrosslinked undrawn HDPE fibers.

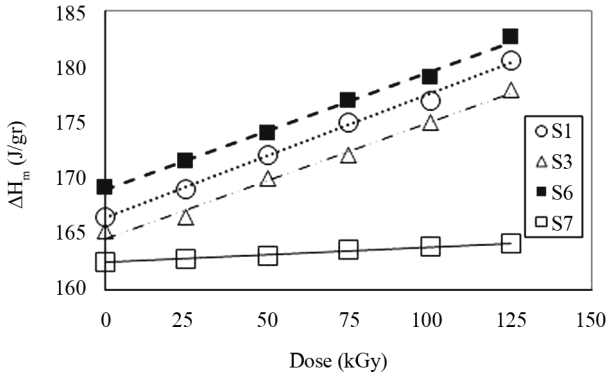

Figure 9. Changes of heat of fusion as a function of irradiation dose for HDPE monofilaments.

crystallinity via irradiation are listed in Table 6. As a result of chain scission, the long chains are replaced by shorter chains which are more readily aligned to give much higher degree of crystallinity [37].

During the first cooling cycle, the presence of crosslinks in the polymer while moving from melt to solid state, disarranges the reorganization and chain folding during the crystallization process.

These changes lead to the formation of imperfect crystallites with smaller size and less content which results in a depression of the heat of crystallization (ΔH_c) as seen in Figure 10.

Mechanical Properties

Tensile stress-at-yield (TY) and tensile stress-at-break (TS) for undrawn and drawn monofilaments are plotted as a function of irradiation dose in Figures 11 and 12, respectively. The tensile strength depends on the polymer structure in a more complicated way. Figure 11 shows a gradual increase in the TY, but, results are different for TS.

In general, some factors are important when the mechanical properties are considered:

- Oxidative degradation leading to main chain scission.
- Oxidation at the boundary region leading to scission

Table 6.Heat of fusion ΔH_m and degree of crystallinity Xc of irradiated HDPE fibers.

Sample	ΔH_m (J/g)	Dose (kGy)	X_c(%)	Dose (kGy)
	0	125	0	125
S1	166.5	180.6	57.41	62.27
S3	165.2	177.9	56.96	61.34
S6	169.1	182.7	58.31	63
S7	162.5	164.1	56.03	56.58

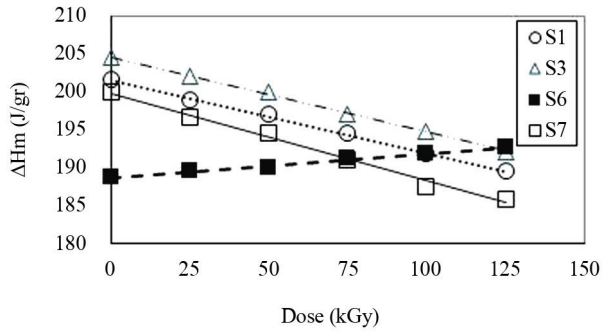

Figure 10. Variation of heat of crystallization as a function of irradiation dose for HDPE fibers.

of the tie molecules.

- Inter- and intra-molecular crosslinking at the crystalline region which take place simultaneously with oxidative degradation in the amorphous region) [37].
- The tensile stress-at-break depends on the polymer draw ability whereas the yield stress of polyethylene is directly related to its degree of crystallinity [25].

Irradiation causes crosslinking and chain scission and the possibility of main chain scission raises with increasing radiation dose.

Generally, by elevating the irradiation dose the TS is increased, but, the results illustrated in Figure 12 reveal that the reduction process has been occurred. The oxidation reaction happened by the presence of oxygen molecules at the irradiation process is the main culprit of this phenomena. If PE irradiation is carried out in the presence of air, radicals formed during irradiation, react with oxygen molecules to form peroxides which eventually lead to polymer chain scission and results in reduced tensile properties. The oxygen molecules

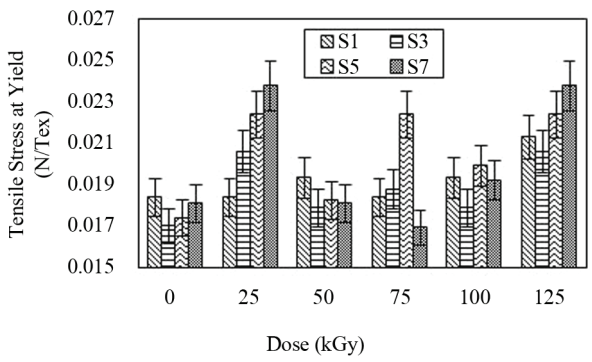

Figure 11. Tensile stress-at-yield versus radiation dose for undrawn irradiated HDPE fibers.

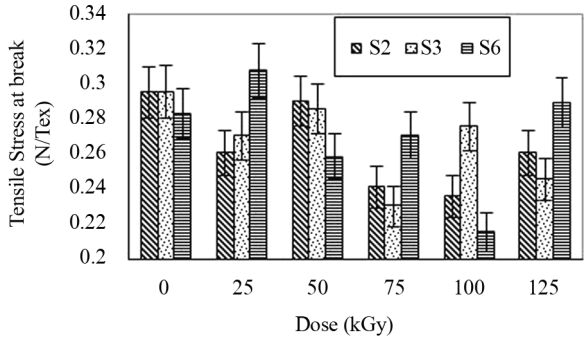

Figure 12. Tensile stress-at-break versus radiation dose for drawn irradiated HDPE fibers.

cannot diffuse into crystallites, hence, chain scission only occurs in the amorphous region [23, 25, and 27].

TS also depends on the unstressed interlamellar tie chains which become stretched upon sample extension, resisting fracture and allowing further extension [15]. In the drawing process, these tie chains become highly oriented. These highly stressed tie molecules undergo chain scission and create free radicals by radiation [32]. These radicals located in the inter – and intra- fibrillar amorphous region react with oxygen molecules and result in depression of TS for drawn monofilaments. In other words, chain scission becomes more dominant with increasing molecular orientation.

As seen in Figures 13 and 14, elongation-at-yield (EY) for undrawn and elongation-at-break (EB) for drawn samples increased with irradiation dose up to 125 kGy. For samples irradiated in the presence of air, oxidative degradation becomes a major process and causes some big network structure destructed and transformed into smaller networks [13, 23]. This phe-

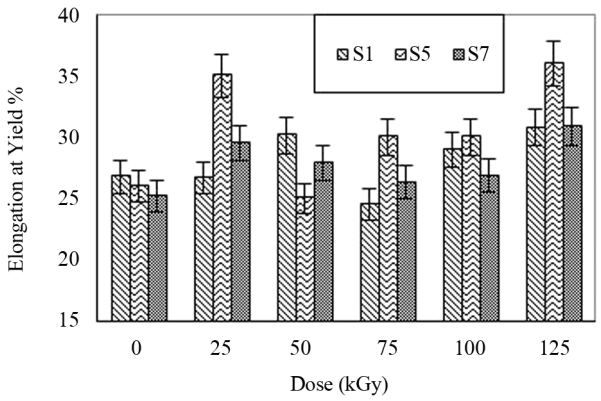

Figure 13. Elongation-at-yield versus irradiation dose for undrawn irradiated HDPE fibers.

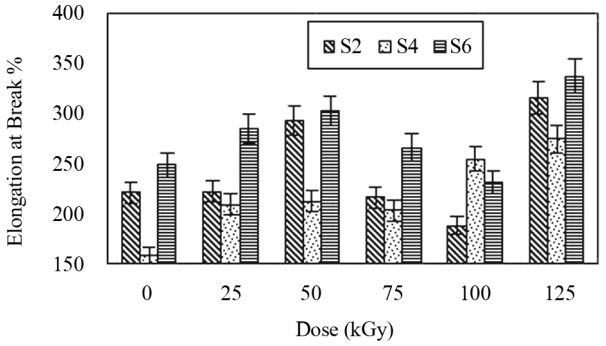

Figure 14. Elongation-at-break versus irradiation dose for drawn irradiated HDPE fibers.

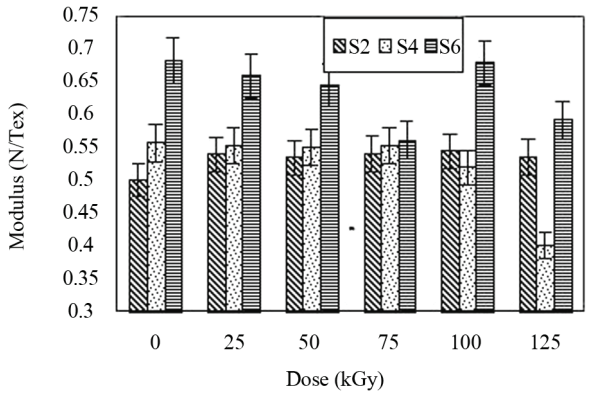

Figure 16. Young's modulus versus irradiation dose for drawn irradiated HDPE fiber.

nomenon includes higher chain mobility and causes slight increase in elongation.

Plots of Young's modulus versus radiation dose for undrawn and drawn monofilaments are shown in Figures 15 and 16, respectively. The effect of crosslinking on the fiber modulus is discussed in terms of the extent of crystalline continuity and the interlamellar contact efficiency [28]. Hence, as seen in Figure 15, we would not expect any changes in modulus for undrawn samples; because, appreciable interlamellar contact and crosslinking which provide crystal continuity is not available.

Drawing process increases the degree of crystallinity and interlamellar interactions. Therefore, it would be expected that crosslinking at the fold surface bundle adjacent lamellae together and providing mechanical continuity which increase the Young's modulus. But oxidative degradation deactivates these consequences and no boosting in the modulus can be seen. The results have been illustrated in Figure 16.

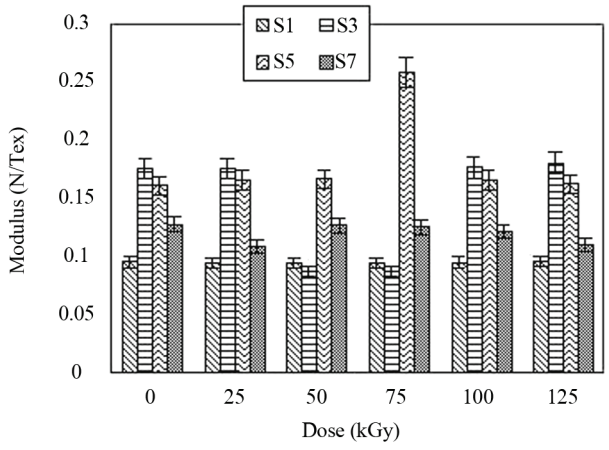

Figure 15. Young's modulus versus irradiation dose for Undrawn irradiated HDPE fibers.

CONCLUSIONS

Electron beam irradiation of polyethylene fibers produces changes in the gel fraction, melting temperature and mechanical properties which are significantly influenced by draw ratio (degree of orientation).

Gel content measurements show that HDPE has been crosslinked by 10 Mev electron beam. The maximum efficiency of crosslinking is 50 % at 75 kGy irradiation dose in the air.

Samples with high draw ratio tend to have higher gel fraction. This effect can be ascribed to the better interlamellar contact via drawing process (λ=7).

Investigation on the thermal properties of irradiated crosslinked polyethylene shows that melting temperature for undrawn high density polyethylene fibers decreases. The increase in T_m with draw ratio can be understood simply in terms of increase in lamella thickness and more interlamellar interactions which results in depression of the melt entropy.

Scissions produced by the reaction of oxygen molecules with radicals at the chain folds and reorganization lead to the formation of the endothermic curves for drawn irradiated monofilament.

Heat of fusion and degree of crystallinity slightly increased upon irradiation for all samples. Heat of crystallization was reduced by boosting irradiation dose.

The decrease in tensile properties was occurred due to the oxidation process, which caused by the presence of oxygen molecules in the system during the ir-

radiation. Elongation-at-break and elongation-at-yield increased for all samples while Young's modulus did not change significantly by increasing the irradiation dose.

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