Nanostructure and Tensile Properties of UHMWPE after a Novel Post-Radiation Thermal Treatment

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Statement of Purpose: Ultra-high molecular weight polyethylene (PE) components of joint replacement prostheses are usually radiation crosslinked to induce wear resistance and then thermally treated to decrease the free radicals induced by the radiation, thereby making the PE oxidation-resistant. In this study, we investigated the effect of a high-temperature post-radiation thermal treatment on the network formation associated with chemical and physical crosslinks (entanglements) in PE. This method has been shown to induce high wear resistance in PE [1, 2]. A study of the resulting nanostructure and its effect on tensile properties showed that the high-temperature thermal treatment was the most effective treatment to induce network formation without compromising tensile properties compared to other thermal treatments.

Methods: Ram extruded GUR 1050 was gamma irradiated to 25, 50 and 75 kGy. Unirradiated rod served as control (PE-Cont). The irradiated rods were then left untreated (PE-As Irr), annealed at 120ºC for 5 hours (PE-Ann), remelted at 150ºC for 5 hours (PE-Melt) or heated to 240ºC (pre-heating, isothermal heating and cooling) for 10 hours (PE-TXL). Crosslink density was characterized in terms of gel content and swell ratio analysis following ASTM D2765 (Method C) using plates weighing 0.39-0.44 g immersed in hot xylene at 130ºC for 4 hours (n =2). A Perkin Elmer differential scanning calorimeter was used to measure crystallinity (n = 3) using a heat of fusion of 293 J/g. Ultra-small angle x-ray scattering was performed at the Advanced Photon Source (Argonne, IL). The lamellar thickness was obtained from the scattering curves using a previously described technique [3]. Tensile specimens (type V ASTM D638) were prepared and stretched (n=6) using an ADMET universal tensile tester operating at a crosshead speed of 10mm/min.

Results: All PE groups had a gel content of 100%, with the exception of PE-Cont, 25kGy PE-As Irr and PE-Ann, (see Table 1). PE-TXL group generally had the lowest swell ratio, which decreased with increase in radiation dose, indicating that it induced the highest network density (effective crosslinks). The crystallinity of PE-Cont was significantly different from all treated PEs ($p<0.05$, ANOVA) except for the 25kGy and 50kGy PE-As Irr. Both melt treatments led to a lower crystallinity and lamellar thickness compared to the as-irradiated and annealed UHMWPEs since crystallization from a highly entangled and crosslinked melt is more difficult. The ultimate tensile strength of the PE-Cont was significantly greater than that of all other PEs except for the 25kGy and 50kGy PE-Ann as well as the 25kGy as-irradiated and 25kGy PE-Melt (see Figure 1). Within each group, the 25kGy irradiated UHMWPEs had a higher ultimate tensile strength ($p<0.05$, ANOVA) than their 75kGy counterparts, with the exception of the TXL group. The PE-Cont had a higher strain-to-break, shown in Figure 2, than the other PEs with the exception of 25kGy PE-Melt. In general, the tensile properties of PE-TXLs were comparable to those of other PE groups.

Conclusion: A high-temperature thermal treatment is more effective in network formation compared to annealing and remelting at moderately high temperatures with a potential for higher wear resistance in joint replacements without compromising tensile properties.

Table 1. Radiation dose (D), Gel content (GC), Swell ratio (SR), Crystallinity (X) and Lamellar thickness (L) for UHMWPE with various heat treatments

Sample ID	D [kGy]	GC [%]	SR	X [%]	L [nm]
PE-Cont	0	85	18	52.3 ± 1.3	31.4
PE-As Irr	25	95	4.34	54.7 ± 1.2	31.1
PE-Ann		99	3.57	56.3 ± 0.5	25.2
PE-Melt		100	3.24	46.6 ± 1.6	22.2
PE-TXL		100	3.05	46.9 ± 2.2	19.1
PE-As Irr	50	100	3.02	55.1 ± 1.8	26.2
PE-Ann		100	3.04	57.4 ± 2.4	28.8
PE-Melt		100	2.64	47.9 ± 1.7	20.8
PE-TXL		100	2.62	44.9 ± 4.6	19.0
PE-As Irr	75	100	2.81	54.4 ± 0.4	26.2
PE-Ann		100	2.64	58.5 ± 0.2	28.1
PE-Melt		100	2.51	47.7 ± 1.0	20.3
PE-TXL		100	2.48	44.9 ± 2.3	18.3

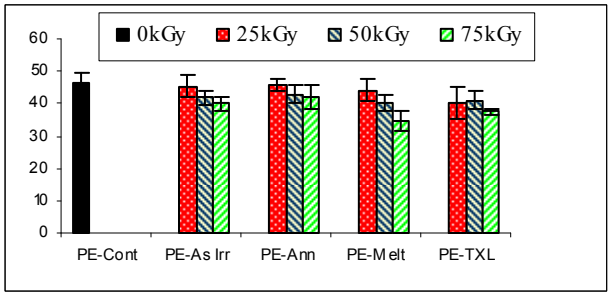

Figure 1. Ultimate Tensile Strength (mean ± standard deviation) of various groups of UHMWPE

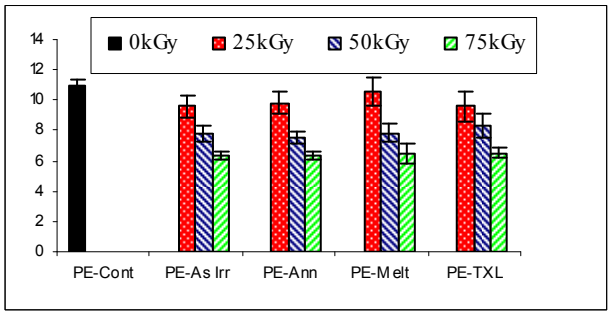

Figure 2. Strain-to-break (mean ± standard deviation) of various groups of UHMWPE

REFERENCES: [1] 2009 SFB Annual Meeting, Paper #66[2] 2009 SFB Annual Meeting, Paper #198[3] Turell ME et al, Biomaterials, 2004, 25:3389-98

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