Oxidation resistant peroxide cross-linked UHMWPE produced by blending and surface diffusion

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Abstract. Ultra-high molecular weight polyethylene (UHMWPE) has been widely used as acetabular cup in total hip replacement (THR) and tibial component in total knee replacement (TKR). Crosslinking of UHMWPE has been successful used to improve its wear performance leading to longer life of orthopedic implants. Crosslinking can be performed by radiation or organic peroxides. Peroxide crosslinking is a convenient process as it does not require specialized equipment and the level of crosslinking can be manipulated by changing the amount of peroxide added. However, there is concern about the long-term stability of these materials due to possible presence of by-products. Vitamin E has been successfully used to promote long-term oxidative stability of UHMWPE. In this study, UHMWPE has been crosslinked using organic peroxide in the presence of Vitamin E to produce an oxidation resistant peroxide crosslinked material. Crosslinking was performed both in bulk by mixing peroxide and resin, and only on the surface using diffusion of peroxides. The results show that UHMWPE can be crosslinked using organic peroxides in the presence of vitamin E by both methods. However, the level of crosslinking decreases with the increase in vitamin E content. The wear resistance increases with the increase in crosslink density, and oxidation resistance significantly increases due to the presence of vitamin E.

1. Introduction
Crosslinking by organic peroxides is used commercially to crosslink different types of polyethylenes by blending into the resin before processing [1]. It is a convenient process as compared to radiation crosslinking as it does not require specialized equipment and the level of crosslinking can be manipulated by changing the amount of peroxides added. Peroxide crosslinking by blending was also used to improve the wear behavior of ultrahigh molecular weight polyethylene (UHMWPE) in vitro for orthopedic implants [2]. However, there is concern about the oxidation of these materials due to possible presence of the by-products of peroxide decomposition. Vitamin E has been successfully used to promote oxidative stability of UHMWPE [3]; however, since it is a free radical scavenger, its addition in the presence of peroxides may disrupt crosslinking [4]. We hypothesized that the desired crosslinking level and oxidation resistance can be achieved by peroxide crosslinking of UHMWPE in the presence of vitamin E.
Limiting crosslinking to the surface is desirable, as crosslinking in bulk leads to decrease in mechanical strength and toughness [5]. We also hypothesized that surface diffusion of peroxides followed by heating to decompose the peroxide could surface cross-link UHMWPE.

2. Experimental

2.1. Materials

**Blending of Peroxides:** Medical grade UHMWPE (GUR 1050) was blended with 0.1 wt% vitamin E. The peroxide was 2,5-di(tert-butylperoxy)-2,5-dimethyl-3-hexyne (P130; Sigma-Aldrich, St. Louis, MO). The peroxide (a liquid at room temperature) was mixed with the vitamin E-blended resin by hand tumbling for 20 minutes. The mixture was compression molded into pucks (10 cm diameter, ~1 cm thickness) under 15-26 MPa for 2 hours. To determine the effect of vitamin E, both virgin and 0.1 wt% vitamin E-blended resins were processed with 1 wt% P130. To determine the effect of consolidation temperature, 0.1 wt% vitamin E-blended UHMWPE was processed with 0.5 wt% P130 at 170, 180, 190, 200 or 210°C.

**Diffusion of Peroxides:** Medical grade UHMWPE (GUR 1050) was mixed with vitamin E at 0.1 wt%, compression molded and cubes (1 cm) were used. Cubes were doped with the peroxide under argon gas and then heated to decompose the peroxides; they were weighed at each step. To determine the effect of doping temperature on cross-linking, cubes (n=3 each) were doped with DCP at 60, 80 or 100°C for 4 hours followed by heating at 130°C for 4 hours. Another set of cubes (n=3 each) were doped with P130 at 80, 100 or 120°C followed by heating at 180°C. To determine the effect of decomposition temperature on cross-linking, cubes (n=3 each) doped with DCP at 80°C for 4 hours were heated at 130 or 140°C. Another set of cubes (n=3 each) doped with P130 at 80°C were heated at 150, 165 or 180°C. Wear testing pins machined from oversized blocks (11×11×15 mm) were doped with DCP at 100°C for 4 hours followed by heating at 130°C for 4 hours, and with P130 at 120°C for 4 hours followed by heating at 180°C for 4 hours. Pins had one doped surface without machining maintained as the wear surface.

2.2. Characterization

**Crosslink Density:** Crosslink density of blended samples was measured by swelling cubes (n=6; 3 mm) in xylene at 130°C. The gravimetric swell ratio was converted to a volumetric swell ratio using the density of polyethylene as 0.94 g/cc and the density of xylene at 130°C as 0.75 g/cc. The cross-link density was further calculated as previously described [6]. In case of diffusion samples surface crosslink density was measured from a surface section (n=6; 1 mm deep and 3×3 mm) swollen in xylene at 130°C.

**Mechanical Testing:** Type V tensile specimens (n=6) according to ASTM D638 were stamped out of 3.2 mm thick sections and then tested at 10 mm/min. Only blended samples were tested. The ultimate tensile strength (UTS) was reported, and true elongation at break (EAB) was determined using a laser extensometer.

**Wear Testing:** Pin-on-disc (POD) wear testing was performed on cylindrical pins (n=3) as previously described at 2 Hz [7] for 1.2 million-cycles (MC). Wear was measured gravimetrically every ~0.16 MC and the wear rate was measured by the weight change from 0.5 to 1.2 MC.

**Oxidative Aging:** Accelerated aging was conducted on 1 cm cubes (n=3) in a pressure vessel at 5 atm oxygen at 70°C for 14 days. Thin sections (150 μm) were micromotom from an inner surface of the cubes, and analyzed using Fourier Transform Infrared Spectroscopy (FTIR) at an interval of 100 μm from the surface along the depth of the sample as an average of 32 scans at a resolution of 4 cm⁻¹. An
oxidation index was calculated by normalizing the absorbance at 1700 cm\(^{-1}\) (1680-1780cm\(^{-1}\)) against that at 1370 cm\(^{-1}\) (1330-1390cm\(^{-1}\)).

3. Results

3.1. Blending of Peroxides

Extensive crosslinking was achieved by adding 1 wt% P130 to both virgin and 0.1 wt% vitamin E-blended UHMWPE (Table 1). But, the cross-link density of the 0.1 wt% blend was less than that of virgin UHMWPE (p<0.0001). As the consolidation temperature increased from 170 to 180, 190, 200 and 210oC for 0.1 wt% vitamin E-blended, peroxide cross-linked UHMWPE, the crosslink density decreased slightly from 0.269±0.007 to 0.256±0.003, 0.250±0.004, 0.245±0.003 and 0.242±0.004 moles/m\(^3\), respectively. The processing temperature in the range of 170-210oC did not have significant effect on the UTS (Fig 1a) or EAB (Fig 1b).

Table 1. Crosslink density, ultimate tensile strength, elongation at break, and average oxidation index of peroxide-crosslinked virgin and 0.1 wt% vitamin E-blended UHMWPEs with 1wt% P130.

|                          | Virgin UHMWPE | 0.1 wt% vitamin E-blended UHMWPE |
|--------------------------|--------------|----------------------------------|
| Cross-link Density, moles/m\(^3\) | 0.343±0.005  | 0.301±0.005                      |
| Ultimate tensile strength, MPa | 32.9±3.8     | 26.7±3.3                         |
| Elongation at Break, %    | 234±17       | 251±15                           |
| Average Oxidation Index   | 0.27±0.05    | 0.04±0.01                        |

Figure 1. (a) Ultimate Tensile Strength and (b) elongation at break of 0.5 wt% Peroxide 130, 0.1 wt% vitamin E-blended UHMWPEs at different processing temperatures.

The wear rate of 0.5 wt% P130, 0.1 wt% vitamin E-blended UHMWPE processed at 180 and 210oC was 1.9±0.3 and 1.8±0.2 mg/MC, respectively. The wear rate of control 0.1 wt% vitamin E sample with no peroxide was 13.6±0.1 mg/MC. After accelerated aging, the average oxidation index of 0.1 wt% vitamin E-blended, 1 wt% peroxide crosslinked UHMWPE was 0.04±0.01 compared to 0.27±0.05 for virgin UHMWPE cross-linked with the same amount of peroxide (Fig 2).
Figure 2. The oxidation index of virgin UHMWPE and 0.1 wt% vitamin E-blended UHMWPE both with 1 wt% Peroxide 130. Three samples of each material were aged in oxygen atmosphere at 70°C under 5 atm pressure for 14 days.

3.2. Diffusion of Peroxides

The crosslink density of DCP-doped samples at 60, 80 and 100°C for 4 hours followed by heating at 130°C for 4 hours was 0.109±0.032, 0.230±0.038, and 0.303±0.020 moles/m³, respectively (Fig 3a). Decomposition of the 80°C-doped sample at 140°C increased the cross-link density to 0.280±0.034 moles/m³. The crosslink density of P130-doped samples at 80, 100 and 120°C followed by heating at 180°C was 0.123±0.010, 0.243±0.022, and 0.348±0.023 moles/m³, respectively (Fig 3b). Increasing the decomposition temperature from 150 to 180°C increased crosslinking (Fig 3b). The weight of DCP-doped cubes (at 60, 80 and 100°C) increased by 0.3, 0.8 and 2.3 wt%, respectively (Fig 4a). After heating at 130°C, 0.06, 0.23, 0.59 wt% peroxide remained (Fig 4a). The weight of P130-doped cubes (at 80, 100 and 120°C) increased by 0.35, 0.95, and 4.6 wt%, respectively (Fig 4b). After heating at 180°C, 0.00, 0.00, and 0.48 wt% peroxide remained (Fig 4b).

Figure 3. Crosslink density of peroxide-crosslinked, vitamin E-blended UHMWPEs processed by diffusion of peroxides. (a) Crosslink density as a function of dicumyl peroxide (DCP) doping temperature and subsequent peroxide decomposition temperature; (b) Crosslink density as a function of Peroxide 130 (P130) doping temperature and subsequent peroxide decomposition temperature.
Figure 4. Weight gain during doping and weight loss during subsequent peroxide decomposition for (a) DCP-doped and (b) P130-doped 0.1 wt% vitamin E-blended UHMWPEs. Doping was performed at the given temperature for 4 hours and decomposition was performed at 130°C for DCP and 180°C for P130.

Wear rate of the 0.1 wt% vitamin E-blended UHMWPE doped at 100°C with DCP and homogenized at 130°C was 1.5±0.9mg/MC. Similar wear rate was observed with the 120°C P130-doped blend that was decomposed at 180°C at 1.6±0.6mg/MC. The wear rate of uncrosslinked 0.1wt% vitamin E-blended UHMWPE was 13.6±0.1mg/MC. After accelerated aging, the average oxidation index (surface 1mm) of DCP cross-linked 0.1 wt% vitamin E/UHMWPE blend (DCP doped at 100°C and decomposed at 130°C) was 0.00±0.062 while that of the virgin sample was 2.81±2.07. The average oxidation index of the P130-doped 0.1 wt% vitamin E/UHMWPE blend (P130-doped at 120°C and decomposed at 180°C) was 2.02±0.05 and that of virgin sample with same doping condition was 3.41±0.11 (Fig 5).

Figure 5. The oxidation index of virgin UHMWPE and 0.1 wt% vitamin E-blended UHMWPE both crosslinked by diffusion of peroxides. (a) Samples DCP doped at 100°C and decomposed at 130°C and (b) samples P130-doped at 120°C and decomposed at 180°C. Three samples of each material were aged in oxygen atmosphere at 70°C under 5 atm pressure for 14 days.
4. Discussion
Our hypothesis that crosslinking using an organic peroxide can be achieved in the presence of an antioxidant free radical scavenger was confirmed with both blended and diffusion samples. Using blending technique with 1wt% P130, even in the presence of vitamin E, led to high crosslink density. The comparatively lower value of the crosslink density of vitamin E blended UHMWPE as compared to the virgin UHMWPE is presumably due to vitamin E’s free radical scavenging ability similar to its effect when using radiation cross-linking [4]. For peroxide cross-linking of polymers, the consolidation has to be optimized to address two main concerns, which are (1) to avoid premature crosslinking that can lead to incomplete consolidation and (2) to ensure stability against oxidation due to peroxide decomposition by-products. The wide range of consolidation temperatures, which resulted in good cross-link density and mechanical properties (Figs 1a and 1b), suggested that P130 was a suitable peroxide for cross-linking UHMWPE with a wide range of processibility. The slight decrease in crosslink density with increasing processing temperature may be due to increased chain scissioning at higher temperatures. Most importantly, the vitamin E-blended, peroxide cross-linked UHMWPE had higher oxidation resistance than the virgin, peroxide cross-linked UHMWPE, which may help enable peroxide cross-linking as a feasible method for fabricating wear and oxidation resistant UHMWPEs for total joint arthroplasty. High levels of cross-linking led to marked improvement in wear rate compared to the uncross-linked UHMWPE, comparable to previously reported wear rates of 100-kGy irradiated and melted virgin UHMWPE (1-2 mg/MC at comparable crosslink density [8]).

Our hypothesis on surface crosslinking that UHMWPE could be cross-linked by diffusing peroxides and elevating the temperature to decompose peroxides tested positive. Surface crosslink density increased with increasing peroxide content, which was increased by the doping temperature (Fig 1a,b). The decomposition temperature (the temperature at which half of the peroxide is decomposed in 1 hour) was 137°C for DCP, which enabled doping and decomposition below the peak melting point of UHMWPE. The decomposition temperature was 152°C for P130, which required decomposition above the melting point of UHMWPE. The crosslinking efficiency of the two peroxides was similar (Fig 1a,b). The achieved crosslink density of peroxide-diffused samples even in the presence of vitamin E was comparable to that of 100-kGy irradiated and melted virgin UHMWPE (~0.26mol/m3), which has excellent wear resistance in vivo [9]. Wear rates of surface peroxide-crosslinked UHMWPEs were lower than their non-crosslinked counterpart, and the wear resistance for the peroxide crosslinked UHMWPEs was dependent on crosslink density. After decomposition, there was a higher amount of DCP remaining compared to P130 (Fig 2a,b), which suggested higher volatility for the by-products of P130. While the presence of these by-products can be a possible source of long-term oxidation of UHMWPE, the negligible oxidation observed after accelerated aging of DCP doped samples supported our hypothesis that vitamin E can improve the oxidation resistance of peroxide cross-linked UHMWPEs. In case of P130, the vitamin E blended sample did show some oxidation on surface but it is appreciably less than the virgin sample, and higher vitamin E content would be required to achieve negligible oxidation. Thus, these results supported our hypothesis that a wear and oxidation resistant UHMWPE could be achieved by cross-linking with both blending and diffusion of peroxides in the presence of vitamin E.

5. Conclusions
 Peroxide crosslinking of vitamin E-blended UHMWPE was achieved by both blending and diffusion techniques, resulting in a wear and oxidation resistant crosslinked UHMWPE. The blending method lead to good mechanical properties material and this may present a convenient and economical alternative of crosslinking UHMWPE for total joint implants. Limiting crosslinking to the surface of vitamin E-blended UHMWPE by diffusion and decomposition of organic peroxides is a new technique, providing a feasible alternative of making a wear and oxidation resistant cross-linked UHMWPE for total joint implants.
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7. References
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