Journal of Biomechanical Science and Engineering

Vol. 1, No. 1, 2006

【Review Paper】

Recent Advances of Mechanical Performance and Oxidation Stability in Ultrahigh Molecular Weight Polyethylene for Total Joint Replacement: Highly Crosslinked and α-Tocopherol Doped*

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Abstract

Ultrahigh molecular weight polyethylene (UHMWPE) is the popular material of choice for use as a bearing surface in total joint replacement (TJR). Despite an extremely low friction coefficient of UHMWPE to metals with liquid lubrication, however, wear and fatigue fractures are major problems limiting the durability of implanted UHMWPE components. Although highly crosslinked UHMWPE has been intensively studied for decades, its use in orthopedic implants has been limited to relatively low stress and multidirectional load applications, such as acetabular cups in hip joint replacements (HJR). This is mainly because highly crosslinked UHMWPE requires thermal treatment process, indispensable for eliminating the residual free radicals, which leads to a decrease in crystallinity resulting in the reduction of fatigue performance of highly crosslinked UHMWPE. By contrast, recently α-tocopherol doped UHMWPE has been viewed seriously as a novel orthopedic UHMWPE. The α-tocopherol doped UHMWPE exhibits excellent wear and fatigue performance and can be applicable to high stress and linear motion applications, such as total knee replacements (TKR). This paper comprehensively reviews recent advances in the mechanical properties and oxidation stability of medical grade UHMWPE, particularly focusing on highly crosslinked UHMWPE and α-tocopherol doped UHMWPE.

Key words: Ultrahigh molecular weight polyethylene (UHMWPE), α-Tocopherol, Crosslinking, Oxidation stability, Oxidation index, Wear, Fatigue, Crystallinity

*Received 19 June, 2006 (No. R-06-0052)
[DOI: 10.1299/jbse.1.107]

1. Introduction

With a rapid increase in aged population and a decrease in a birthrate, the society of Japan as well as other advanced nations has come to an aged society in the 21st century. To date, many aged people suffer from debilitating diseases such as osteoarthritis (OA) and rheumatoid arthritis (RA), the number of which will increase more and more in the near future. Nowadays, a joint replacement is one of treatments to ease chronic pain in these kinds of arthritis. In the United States, estimated half million total joint replacements (TJR) were performed in 1995[1], most of which were total hip replacements (THR) and total knee replacements (TKR). According to the Nationwide Inpatient Sample on joint replacements, performed between 1990 and 2003, primary and revision procedures have doubled in TKR [2]. In contrast, primary and revision procedures in THR, although not so severely as those in TKR, have increased by 30%, and 60%, respectively [2]. The success of a joint replacement lies not only with the skill of an orthopedic surgeon but also with the mechanical performances and oxidation stability of materials used in TJR.

Ultrahigh molecular weight polyethylene (UHMWPE) is the popular material of choice for use as a bearing surface in total joint replacement (TJR). Biomedical use of UHMWPE was originated as acetabular cups in THR [3], and was applied later to TKR [4, 5]. As wear has been major damage limiting the longevity of implanted UHMWPE acetabular cups in THR, quite a few efforts have been made mainly to improve the wear performance of UHMWPE components. Consequently, several alternate or enhanced UHMWPEs have been proposed and the wear-resistance of UHMWPE has been resultantly improved. During the struggle for advancing the wear-resistance of UHMWPE, however, improvement of fatigue performance of UHMWPE was of secondary importance.

Flaking-like fracture so-called delamination has often been reported in retrieved UHMWPE knee components [6-11]. Delamination, a kind of fatigue damage, typically observed in retrieved UHMWPE knee components have been recognized as a primary cause of revision surgery in TKR. Oxidation has been known to adversely affect the mechanical properties of UHMWPE, resulting in enbrittlement[12] and fatigue damage of UHMWPE[13, 14]. It is thus no exaggeration to say that efforts to solve the wear and fatigue damage problem in orthopedic UHMWPE is exactly the struggle for the improvement of oxidation stability of UHMWPE. After the abandonment of the process of γ-sterilization in air, a major cause of the oxidative degradation of UHMWPE, in all of the major UHMWPE manufacturers in the United States in 1998, many sterilization methods have been proposed and have practically been conducted; γ-sterilization with an oxygen scavenger, γ-sterilization in inert gasses or in vacuum package[15, 16], ethylene oxide gas[17], and gas plasma[18] and so on. At the same time, recently, engineering and orthopedic researchers have developed highly crosslinked UHMWPE and α-tocopherol doped UHMWPE, promising alternative biomaterials in TJR.

This paper provides a comprehensive review of recent advances in mechanical properties, macromolecular structures and oxidation stability of medical grade UHMWPE used for total joint replacements, particularly focusing on highly crosslinked UHMWPE and α-tocopherol doped UHMWPE. The first part of this article outlines the oxidation of UHMWPE. This part gives a help to understand the concept of material designing and the feature of the mechanical performance of highly crosslinked UHMWPE and α-tocopherol doped UHMWPE in later parts. The second part reviews the development and properties of highly crosslinked UHMWPE. Finally the third part reviews the development and properties of α-tocopherol doped UHMWPE.

2. Oxidation of UHMWPE

Oxidative degradation is one of the main problems of orthopedic UHMWPE[19, 20], which adversely affects the mechanical performances of UHMWPE [21]. Oxidation of linear polyethylene caused by irradiation has been known since 1948[22]. In contrast, the effect of γ-irradiation on the oxidation of UHMWPE components in orthopedic implants has been discussed since the late 1970s[23]. The oxidation of orthopedic UHMWPE is usually induced by sterilization with high-energy radiation, such as γ rays and electron beam irradiation.

2.1 Oxidation process of UHMWPE

As schematically shown in Fig. 1[24], oxidation process of UHMWPE can be explained by the formation of free radicals and their subsequent series of reaction with oxygen. The formation of alkyl radicals (denoted by Radical (I) in Fig. 1) and their reaction with oxygen is the key step in series of the oxidation process. Subsequently this reaction gives birth to peroxy radicals, which in turn extract hydrogen atoms from adjacent UHMWPE molecules to form hydroperoxides and new alkyl radicals. The new alkyl radicals formed in turn participate in the cycle of a series of free radical formation and reaction with oxygen. Moreover new radicals can be generated from hydroperoxides because they are quite unstable and are easy to be decomposed by light, heat, and mechanical stresses.

Typical changes that appear in macromolecular structures during the oxidation process of UHMWPE are molecular chain scission and crosslinking. In the case of linear polyethylene, it has been observed that crosslinking predominates after γ-irradiation in the absence of oxygen, whereas oxidative degradation due to chain scission predominates after γ-irradiation in the presence of oxygen. As well as linear polyethylene, UHMWPE generally exhibits almost the same tendency on the oxidative change in the molecular structure.

2.2 Post-irradiative oxidation

Oxidation process of UHMWPE can be classified into two types, oxidation during irradiation and post-irradiative oxidation. The oxidation process explained in the previous subsection is a general process of oxidation, which can be of course applicable to both the oxidation processes of UHMWPE. What is typically observed in post-irradiative oxidation of UHMWPE is over-concentrations of residual free radicals at a certain local region, residual free radicals may migrate from crystalline regions to crystalline/amorphous

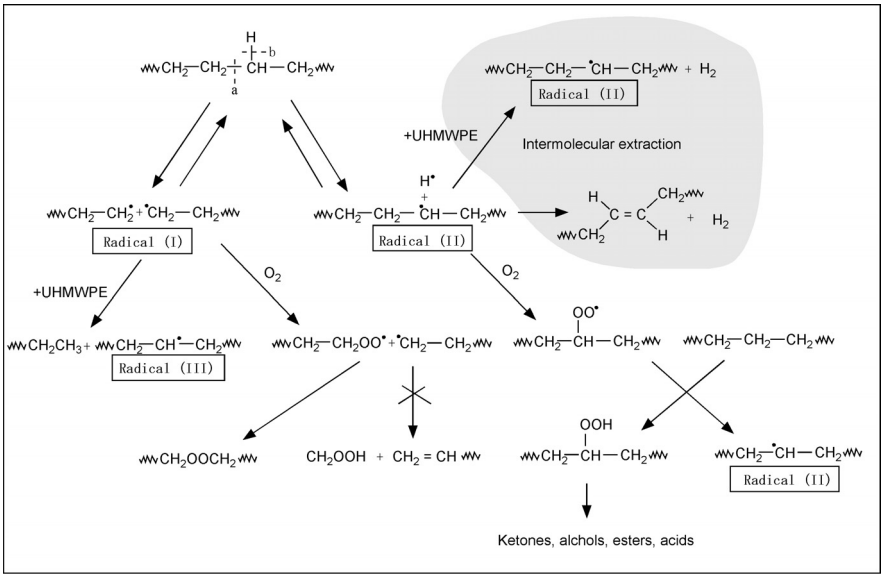


Fig. 1 Schematic diagram of oxidation process of UHMWPE induced by irradiation.

interfaces before leading to oxidation products. Although, incorporation of antioxidative α-tocopherol into UHMWPE (mentioned later in Section 4) is effective in oxidation during irradiation, α-tocopherol is usually located in amorphous regions. In this respect, α-tocopherol in UHMWPE may not effectively scavenge free radicals in the vicinity of the interfaces.

3. Highly crosslinked UHMWPE

3.1 History of crosslinked UHMWPE

Crosslinking of polyethylene has been a well-known technique to improve abrasive wear resistance of polyethylene for industrial use since 1960s[26-28]. In contrast, only a few papers have reported the application of crosslinking technique to polymers for orthopedic use in joint arthroplasty[29-32]. In later 1990s, many researchers in orthopedic communities have reported that crosslinked UHMWPE exhibits a drastic decrease in the wear rate in multi-directional hip simulators[33-38]. Since then crosslinked UHMWPE has been the most popular material of choice as acetabular cups in THR.

According to crosslinking methods, crosslinked polyethylene can be classified into three types, crosslinked by ionizing radiation, chemically crosslinked by peroxide, and by silane[27, 28]. Ionizing radiation includes γ-irradiation with a standard dose of 25 to 40kGy used for sterilization[1], which forms free radicals in polymers. Especially in UHMWPE, some of the free radicals react with each other to form crosslinks and trans-vinylene bonds while others remain reactive in the material for a long time. It has been known that γ-irradiation with a high dose of 50 to 100kGy forms highly crosslinked UHMWPE[39]. Other crosslinking methods use organic peroxide[27, 28] or silane chemistry[40, 41]. The choice of resin and crosslinking methods affects the morphology, crystallinity, consolidation behavior, and hence the mechanical properties of UHMWPE. The difference among them has been reviewed in detail by Kurtz et al.[1]. Almost all the crosslinked UHMWPEs used nowadays for TJR are highly crosslinked with radiation dose. This is mainly because chemically crosslinked UHMWPE have shown to result in oxidation and enbrittlement in an accelerated aging study[42]. Therefore, the term "highly crosslinked UHMWPE" described in this paper, denotes UHMWPE crosslinked highly with γ-irradiation or electron beam radiation hereafter.

3.2 Oxidation stability

As described in Subsection 3.1, radiation crosslinking results in the formation of free radicals. Some of the free radicals formed react with each other to form crosslinks and trans-vinylene bonds. In contrast, the remainders are highly reactive in UHMWPE for a long period of time. The long-term oxidation stability in radiation crosslinked UHMWPE can be obtained by imposing thermal treatment on irradiated UHMWPE. It has been reported that the thermal treatment process after irradiation reduces the concentration of the residual free radicals resulting in the improvement of long-term oxidation resistance of UHMWPE.

Various thermal treatment methods have been proposed in combination with a variety of crosslinking methods. Premnath et al. have examined the oxidation stability of HUMWPE that was heated to 140 °C and crosslinked in the molten state using electron beam irradiation by an absorbed dose of 200 kGy[43]. They concluded that no alkyl or allyl residual free radicals were detected. McKellop et al. examined the wear and oxidation stability of UHMWPE that was γ-irradiated in the solid state and remelted to minimize free radicals[35]. The oxidation stability of UHMWPE manufactured using this remelting method has been reported to be excellent[35, 37]. Recently Muratoglu et al. have reported a thermal treatment method to increase the crosslink density of UHMWPE in which UHMWPE is irradiated in air at an elevated temperature with a high-dose-rate electron beam and

subsequently is melt-annealed[44]. This method resulted in the absence of detectable free radicals in UHMWPE and, as a result, excellent resistance to oxidation of the polymer.

3.3 Mechanical property

Generally, elastic properties (Young's modulus and yield stress) are affected by the morphology of the crystalline phase while plastic properties (ultimate tensile strength and elongation at break) by the morphology the amorphous phase of UHMWPE. As summarized in Table 1, the physical and mechanical properties of UHMWPE vary diversely, depending on the manufacturer, the grade, and putting it in an extreme way, the lot of the material. In this respect, excessive comparison of mechanical properties of one type of UHMWPE with those of another type does not make any sense[45]. This is mainly because polymers, as UHMWPE does, generally comprise a hierarchical structure of molecules, each element of which, depending on processing conditions, such as pressure, temperature, a resin type, and so on, influencing with each other, contributes complicatedly to the emergence of mechanical properties of bulk polymers. The most important pieces of information, available to evaluate the mechanical performances of a certain orthopedic UHMWPE for use, are wear performance and fatigue performance often connected with crystallinity[45].

Increase in crosslinking, obtained by increased radiation dose, adversely affects uniaxial ductility of UHMWPE[47]. Grobbelaar et al. observed a 30% increase in the wear resistance of the crosslinked UHMWPE. However, the impact strength and the elongation at break were observed to decrease with increasing radiation dose[30]. Kurtz et al. have reported that the uniaxial failure strain of UHMWPE decreases linearly with increasing radiation dose[47].

Thermal treatment after irradiation can adversely affects mechanical properties of UHMWPE, too. For example, a new form of UHMWPE that was heated to 140 °C and crosslinked in the molten state using electron beam irradiation resulted in significant decreases in the yield stress, ultimate tensile strength, and elongation at break in spite of no detectable wear rate measured[48]. Luisetto et al. examined changes of mechanical properties due to accelerated aging in γ-irradiated UHMWPE thermally treated at a temperature higher than the melting point. They concluded that the thermal treatment adversely affected the mechanical properties (the ultimate tensile strength and elongation at break) of crosslinked UHMWPE after accelerated aging. Kurtz et al. have reported the effect of post-irradiation thermal treatment on uniaxial mechanical properties of UHMWPE[49]. At a dose of 100kGy, the yield stress and the ultimate stress of 150°C- remelted UHMWPE were significantly lower than those of UHMWPEs annealed at 110°C and at 130°C. In contrast, the elongation at break of 150°C-remelted UHMWPE was significantly higher compared to that of 110°C -annealed and 130°C-annealed UHMWPEs, respectively.

Table 1 Typical average of physical and mechanical properties of UHMWPE[46].

Property	Value
Molecular weight (10^6 g/mol)	2-6
Melting temperature (°C)	125-138
Poisson's ratio	0.46
Specific gravity	0.932-0.945
Tensile modulus of elasticity (GPa)	0.8-1.6
Tensile yield strength (MPa)	21-28
Tensile ultimate strength (MPa)	39-48
Tensile ultimate elongation (%)	350-525
Impact strength, Izod (J/m)	>1070
Degree of crystallinity (%)	39-75

Table 2 Effect of post-irradiation thermal treatment on uniaxial mechanical properties of UHMWPE at a dose of 100kGy irradiation.

Thermal treatment	Yield stress (MPa)	Ultimate stress (MPa)	Elongation at break (%)
None	23.2±0.2	47.6±2.0	238±13
110°C -annealed	23.0±0.3	47.3±1.5	230±12
130°C-annealed	22.6±0.2	48.5±1.5	231±13
150°C-remelted	19.5±0.3	43.9±3.9	246±12

3.4 Wear performance

As depicted in Subsection 3.1, crosslinking has been a well-known technique to improve wear resistance of polyethylene for industrial use for decades. Thus many reports have exhibited the improvement of wear resistance in highly crosslinked UHMWPEs that include various combinations of crosslinking conditions with thermal treatment methods[30, 33, 50-55]. Radiation crosslinked UHMWPE shows the improvement of wear resistance[30, 33]. Particularly irradiation to a dose of 100kGy has been demonstrated to decrease wear substantially. Muratoglu et al. have shown that the wear rate of highly crosslinked UHMWPE dramatically decreased as a function of increasing radiation dose[56]. Moreover, No wear region was observed at dose of 150kGy. Tang et al. have examined the wear resistance of UHMWPE crosslinked by organic silane[51]. The wear resistance of UHMWPE was improved at a low content of organic silane. However, at a high content of organic silane, the wear resistance was reduced.

Thermal treatment, indispensable for elimination of the residual free radicals formed by irradiation, can adversely affect the wear performance of accelerated aged UHMWPE. Muratoglu et al. showed a drastic increase in the wear rate of 105kGy-irradiated and annealed UHMWPE following three weeks of accelerated aging at 80 °C in air[56]. This may be partly because the annealing process at a certain temperature is not appropriate for UHMWPE to be stable for oxidation. In contrast, 100kGy-iradiated and remelted UHMWPE showed an excellent wear resistance after accelerated aging, equal to that before aging.

Wear performance of highly crosslinked UHMWPE depends on relative motion patterns between UHMWPE surfaces and the counter-surface of metals. Wang et al. have reported that although radiation crosslinked UHMWPE with a dose of up to 100kGy could reduce the wear rate in a multi-directional hip simulator, the wear rate in a knee simulator was not reduced[34]. This result has been the strong motive for limiting the application of highly crosslinked UHMWPE to THR.

3.5 Fatigue performance

Although crosslinking exhibits promise for improvement of wear resistance of UHMWPE, crosslinking can adversely affect the fatigue performance of UHMWPE. A low crosslink density is recommended to obtain the optimal fatigue resistance from both a crack initiation and propagation standpoint[57, 58]. The radiation crosslinking at 100 and 150 kGy has been reported to significantly reduce the fatigue strength of highly crosslinked UHMWPE, which was reduced by another 20% due to subsequent remelting at 100kGy[59, 60]. This is presumably because the remelting process subsequent to irradiation eliminates the crystallites and allows the recombination of the trapped residual free radicals to form crosslinks, which prevents chain mobility resulting in decrease in crystallinity[61].

Fatigue performance of UHMWPE is much more important than wear performance particularly in high stress applications such as knee joints. In TKR, fatigue crack initiation and propagation resistance are concerns in tibial inserts, continuously exposed to large cyclic stresses, where the initiation and growth of subsurface cracks potentially contribute

to delamination[62]. If the application of highly crosslinked UHMWPE is to be extended to TKR, improvement of fatigue resistance has to be seriously studied.

3.6 Problems and Future study

As described in the previous subsection, a major drawback of highly crosslinked UHMWPE is apparently fatigue performance, which is a potential trade-off to wear resistance. The remelting process after irradiation causes a decrease in crystallinity, which adversely affects the mechanical properties and fatigue strength of highly crosslinked UHMWPE[63]. Recent studies have reported the improvement of the mechanical properties, crystallinity, and fatigue strength of highly crosslinked UHMWPE compressed under a high pressure. The novel methodology of high pressure crystallization can be a promising alternate to the remelting process[64, 65].

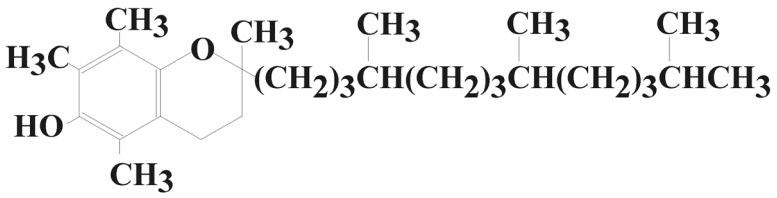
Another hot topic on studies of highly crosslinked UHMWPE is the necessity of crosslinking itself as means of improving wear resistance of UHMWPE[66]. Oral et al. examined the tensile mechanical properties and wear rate of α-tocopherol doped conventional UHMWPE following high pressure crystallization[66]. The α-tocopherol doped and high-pressure crystallized UHMWPE showed significantly lower wear and higher mechanical properties than non-irradiated UHMWPE. These results may suggest the possibility of highly crosslinked UHMWPE displaced by α-tocopherol doped UHMWPE in the near future.

4. α-Tocopherol doped UHMWPE

4.1 Chemical aspect of α-tocopherol

α-Tocopherol, a yellow-brown lipidic substance with a high viscosity, is a natural antioxidant and has often been used as a preservative in food industry. As shown in Fig. 1 the chroman head is responsible for abstracting and stabilizing free radicals within the structure. Thus α-tocopherol acts as a scavenger for residual free radicals generated by irradiative oxidation of UHMWPE, which eliminates the long-term adverse effects of post-irradiated oxidation that may occur before implantation (called shelf-aging) and in vivo after implantation. The long chain called 'phytyl tail' provides biocompatibility with UHMWPE. The antioxidant mechanism of α-tocopherol on lipids has been explained in reference [67]. The donation of the phenolic hydrogen on the chroman ring in α-tocopherol to the oxidized molecule spares free radicals on lipids, such as peroxy and alkyl radicals, from further reaction.

The extraction of the hydrogen atom on the chroman ring occurs mainly by the peroxy radicals rather than by alkyl radicals[68, 69]. Thus if there exists oxygen available, the alkyl radicals react preferentially with oxygen to generate a peroxy radical, which in turn extracts a labile hydrogen to form a hydro peroxide and a phenoxy radical[70]. The phenoxy radical is subjected to steric hindrance, which makes itself stable and remains in the polymer, stopping the oxidation process.



α - Tocopherol

Fig. 2 Molecular structure of α-tocopherol.

4.2 Incorporation method of α-tocopherol into UHMWPE

There exist two methods of incorporation of α-tocopherol into UHMWPE reported in literatures[59,71]. One is to mix α-tocopherol with UHMWPE powder prior to consolidation[71]. The other is to take advantage of the diffusion of α-tocopherol into bulk UHMWPE[59]. The former method, originally proposed to stabilize oxidation caused by γ-irradiation in air, has mainly two advantages superior to the latter methods (1) in that the distribution of α-tocopherol concentrations in UHMWPE can be controlled uniform enough, and (2) that α-tocopherol concentrations in UHMWPE can be controlled to an arbitrary percentage content. Recently crystallization method has been proposed to apply to α-tocopherol doped UHMWPE powder.

4.3 Oxidation stability

The antioxidative effect of α-tocopherol on UHMWPE can be estimated by calculating the oxidation index from FTIR transmission spectra. The oxidation index measurement for orthopedic UHMWPE has been regulated in ISO 5834-4. As shown in Fig. 3, the oxidation level of α-tocopherol doped UHMWPE is extremely lower than that of conventional γ-irradiated UHMWPE even after accelerated aging regulated in ISO 5834-3. In other words, the oxidation index curve as a function of time spent after irradiation rapidly increases in γ-irradiated UHMWPE, whereas the oxidation index curve in α-tocopherol doped γ-irradiated UHMWPE increases extremely slow. Thus the initial control of oxidation stability allows the excellent long-term oxidation stability of UHMWPE.

α-Tocopherol, incorporated in UHMWPE, reacts with peroxy radicals formed during γ-irradiation. This reaction forms quinone groups from α-tocopherol [72-74]. Different quinones have been reported to be formed, depending on the concentration of α-tocopherol[72]. Mallégol et al. have estimated the percentage content of α-tocopherol required as about 0.075wt% in every dose of 10kGy with γ-rays[72]. According to this estimate, conventional (25kGy) γ-irradiated UHMWPE requires the 0.19wt% α-tocopherol to stabilize the oxidation process during γ-irradiation. In this respect, this rough estimate, although obtained from only chemical consideration, have good agreement with the percentage content of 0.1-0.3 wt% α-tocopherol in conventional (25kGy) γ-irradiated UHMWPE samples, empirically obtained from consideration of the mechanical properties required [71,75].

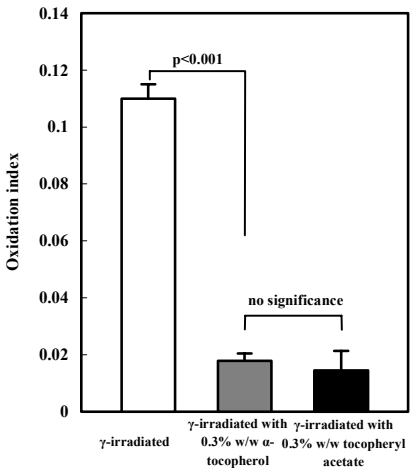


Fig. 3 Oxidation index obtained from IR transmission spectra. All UHMWPE samples were exposed to accelerated aging[76].

4.4 Mechanical property

As described in Subsection 3.3, elastic properties (Young's modulus and yield stress) are affected by the morphology of the crystalline region while plastic properties (ultimate tensile strength and elongation at break) by the morphology of the amorphous region of UHMWPE.

One of the remarkable features observed in plastic behavior of α-tocopherol doped UHMWPE is an increased elongation at break compared to those in highly crosslinked and undoped conventional UHMWPEs[66,77]. This feature can be understood by comparing the morphology of the amorphous region with each other. In crosslinked UHMWPE, many crosslinks have been formed mainly at the amorphous region, which reduces molecular chain mobility under plastic deformation. In contrast, α-tocopherol doped UHMWPE has much less crosslinks than crosslinked UHMWPE because α-tocopherol acting as a radical scavenger, hinder the formation of crosslinking as well as oxidative chain scission. In consequence, α-tocopherol doped UHMWPE has much chain mobility compared to crosslinked UHMWPE, exhibiting ductility in the mechanical performance of the bulk material.

In elastic behavior, the elastic modulus and yield stress of α-tocopherol doped UHMWPE is prone to slightly increase compared to that of undoped irradiated UHMWPE[66,77]. This feature can be explained by the fact that incorporation of α-tocopherol into UHMWPE shows an increase in crystallinity. It has been known that the mechanical properties describing elastic deformation behavior directly depend on the crystallinity.

4.5 Wear performance

Wear performance of α-tocopherol doped UHMWPE is extremely excellent under unaged and accelerated aged conditions, compared to that of γ-irradiated UHMWPE and is comparable to that of highly crosslinked UHMWPE.

Surface roughness values of α-tocopherol doped UHMWPE samples, measured in a two-dimensional sliding test with a rectangular U-shaped sliding pathway, has been reported to be extremely lower than those of non-irradiated and γ-irradiated UHMWPE samples (Fig. 4)[62]. According to surface observation with a microscope, α-tocopherol doped UHMWPE samples have exhibited initial machine tracks at the surface even at the sliding number corresponding to that at which precursors of delamination have begun to be observed in γ-irradiated UHMWPE samples (Fig. 5).

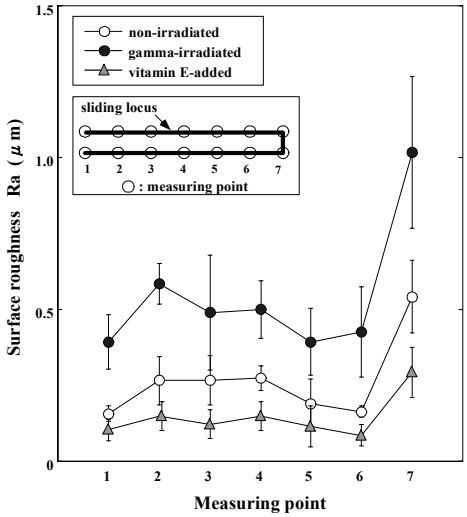


Fig. 4 Surface roughness (Ra) of three types of UHMWPE samples measured at the sliding number of 50,000 in a two-dimensional sliding test[62].

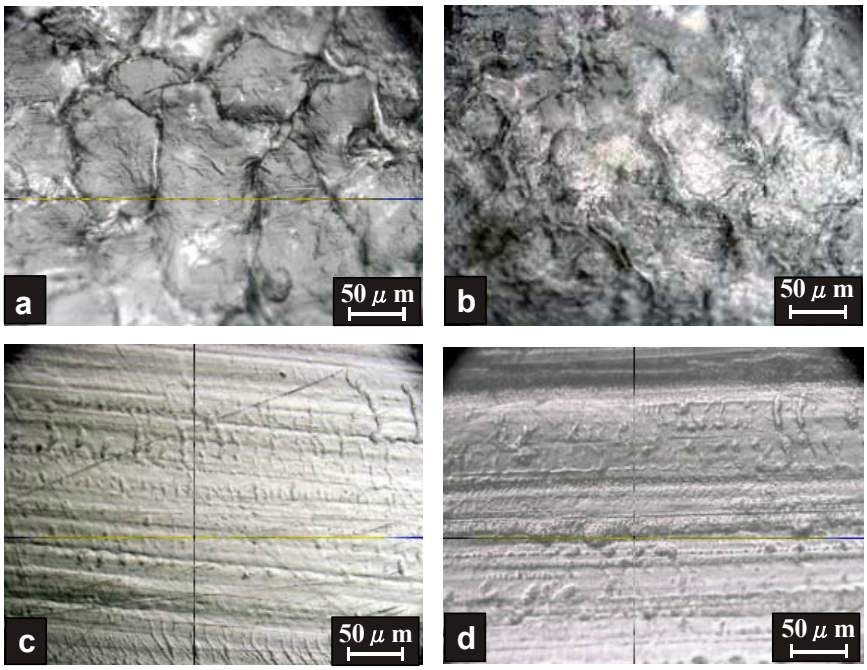


Fig. 5 Microscopic images of sliding surfaces at (a) the sliding number of 25,000 in γ-irradiated, (b) the sliding number of 50,000 in γ-irradiated, (c) the sliding number of 25,000 in 0.3wt% α-tocopherol and γ-irradiated, and (d) the sliding number of 50,000 in 0.3wt% α-tocopherol and γ-irradiated UHMWPE observed in a two-dimensional sliding test[62].

Table 3 The percentage content of crystalline regions of UHMWPE[76].

Sample type	Crystallinity (%)
γ-irradiated	57.5±1.16
0.3wt%α-tocopherol doped and γ-irradiated	60.3±0.72

Also, The wear rate of α-tocopherol doped UHMWPE samples[59], measured in a pin-on-disc wear test, has been reported to be comparable to the wear rate of contemporary highly crosslinked UHMWPE samples[78]. Moreover the wear rate of α-tocopherol doped UHMWPE samples was extremely low than that of conventional γ-irradiated (in nitrogen gas) UNMWPE samples under unaged and accelerated aged conditions.

The mechanism of improved wear resistance due to incorporation of α-tocopherol remains to be elucidated. Some possible reasons include that α-tocopherol belongs to lipids, which might effectively contribute to excellent lubrication, and that incorporation of α-tocopherol into UHMWPE increases the content of crystalline regions (Table 3).

4.6 Fatigue performance

Although fatigue performance of UHMWPE is usually characterized by the fatigue crack initiation and propagation, addition of α-tocopherol exhibits promise particularly for fatigue crack initiation. Fatigue fracture of UHMWPE has been reported to set up from microscopic subsurface crack initiation (Fig. 6). The microscopic cracks are prone to initiate at subsurface grain boundaries[62]. In the next stage, some micro cracks are propagated and are connected with each other to grow into macroscopic cracks. Shibata et al. have shown that α-tocopherol doped and γ-irradiated UHMWPE dramatically retards micro and hence macro crack initiation compared to γ-irradiated UHMWPE (Fig. 7).

The stress intensity factor range at fatigue crack initiation has been examined for α-tocopherol doped UHMWPE[59, 79]. The stress intensity factor range at fatigue crack initiation of α-tocopherol doped and irradiated UHMWPE exhibited higher than that of undoped highly crosslinked UHMWPE. In contrast, the stress intensity factor range at

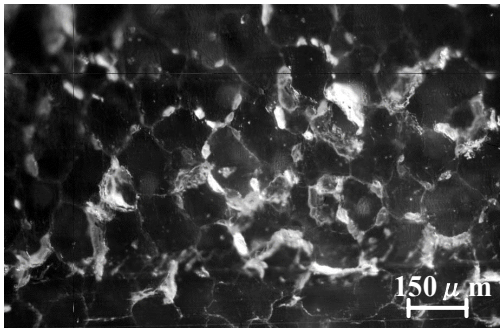


Fig. 6 Micrograph of subsurface cracks observed at the sliding number of 25,000 in γ-irradiated UHMWPE in a two-dimensional sliding test[62].

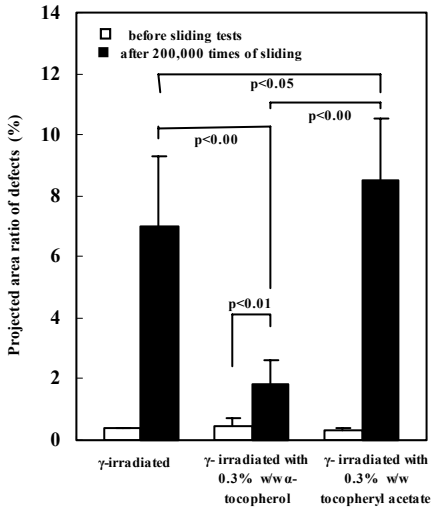


Fig. 7 Projected area ratios of internal defects just below the sliding surfaces[76].

fatigue crack initiation of α-tocopherol doped and γ-irradiated UHMWPE did not show significant difference from that of conventional γ-irradiated and unirradiated UHMWPEs. These results were obtained using pre-notched CT specimens. In this respect, this type of testing can take only macro crack propagation into consideration.

4.7 Biocompatibility and bioactivity of α-tocopherol

α-Tocopherol is a biocompatible stabilizer for orthopedic UHMWPE[80]. However cytotoxicity testing showed decreases in adhesion rate of cells and cell spreading in spite of no cytotoxic behavior of α-tocopherol doped UHMWPE. In contrast, Rèno and Cannas have examined adsorption testing of immunoglobulin G (IgG) responsible for macrophage adhesion and activation, resulting in a decrease in IgG adsorption[81]. They concluded that the surface of α-tocopherol doped UHMWPE are potentially apt to be less reactive to foreign body than undoped UHMWPE.

Effects of α-tocopherol on metal ingredients included in metal counter-components used in TJR are also important to be considered. However little information is available on this problem. McKay et al. have reported that α-tocopherol partially prevented nickel-induced toxicity (as assessed by alkaline phosphatase activity)[82]. By contrast, Husain et al. has reported that α-tocopherol exacerbates nickel toxicity in mice[83]. Biological testing is inevitable for launching clinical use of α-tocopherol doped UHMWPE for components of orthopedic implants. In this respect, further biological studies on incorporation of α-tocopherol into UHMWPE will be seriously required in the near future.

5. Summary

The aim of this review was to summarize pieces of the state of the art information on medical grade UHMWPE for use in total joint replacements, especially focusing on advances in mechanical properties and oxidation stability of highly crosslinked UHMWPE and α-tocopherol doped UHMWPE.

In the past one decade, highly crosslinked UHMWPE has been intensively studied by many engineering and orthopedic researchers for its excellent wear resistance. Consequently, many total hip replacements that include both primary and revision surgery, using highly crosslinked UHMWPE, have been performed all over the world. At present, some retrieval studies on highly crosslinked UHMWPE have already begun to be reported. Retrieval studies on highly crosslinked UHMWPE acetabular cups reported in the next ten years might spur numerous studies into the molecular structure, crystalline morphology, wear and fatigue performance of highly crosslinked UHMWPE.

α-Tocopherol has been shown to be highly promising for the long-term oxidation stability of UHMWPE. Although α-tocopherol may slightly hinder the radical process of crosslinking, it can be recommended as a biocompatible stabilizer for orthopedic UHMWPE. In 2006, clinical trials on total joint replacements using α-tocopherol doped UHMWPE components are now under way in Japan. In the near future, problems concerning ISO 8432-1, 8432-2, and ASTM F648 that define the requirements for medical grade UHMWPE powder and forms will have to be seriously considered to modify the regulations to include UHMWPE containing α-tocopherol.

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