The effects of strain rate and low-gamma irradiation on the compressive properties of UHMWPE

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Abstract. The effects of strain rate and low-gamma irradiation on the compressive properties of ultra-high molecular-weight polyethylene (UHMWPE) were investigated. Gamma irradiation was performed at 30 kGy in nitrogen or at 29 kGy in air without post-irradiation treatment. Quasi-static and impact compressive tests using the split-Hopkinson pressure-bar technique were performed to measure stress–strain relations up to a true strain of 8% at strain rates of between 0.0004 and 260 s^{-1}. For both unirradiated and gamma-irradiated UHMWPE specimens, an increase in the strain rate significantly increased the Young's modulus and the 0.5% yield stress. Gamma irradiation in air significantly increased the Young's modulus, as determined by quasi-static and impact compressive testing, and the 0.5% yield stress, as determined by impact compressive testing. The strain-rate dependence in the power-law relationship was similar to that observed for strain rates ranging from 0.02 to 0.10 s^{-1} (Kurtz et al., *Biomaterials* **23**, 2002, pp. 3681–3697).

Keywords: Gamma irradiation, impact compressive testing, strain rate, ultra-high molecular-weight polyethylene

1. Introduction

Ultra-high molecular-weight polyethylene (UHMWPE) has been used as a load-bearing articular component of artificial joints for over three decades. However, it has been recognized that wear, fatigue and plastic deformation of the UHMWPE components affect the lifetime of joint arthroplasties. The current technical approach to improving the longevity of UHMWPE components includes optimization of the geometry in order to achieve a favorable stress state and relative motion between the components that are in contact. Finite element analysis is the most commonly used methodology to simulate the mechanical response of artificial joints, in order to optimize the implant design. This numerical method, which started with a static elastic analysis under a fixed joint position, has achieved the prediction of dynamic stress distributions within a standard [1,14] or abnormal [14] gait cycle. However, although polymeric materials generally exhibit strain-rate sensitivity, current constitutive models for UHMWPE have not

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been verified with dynamic loads. Thus, a dynamic constitutive model should be established in order to achieve reliable and accurate dynamic stress and strain predictions.

Gamma irradiation of UHMWPE is of great interest because it has a sterilization effect and causes crosslinking of the polymer that is believed to improve its wear resistance [7]. Although alternative sterilization methods, such as ethylene oxide (ETO) and e-beam irradiation, are available, gamma-irradiation sterilization has continued to be the method of choice because of its high efficiency and simplicity. In addition, a higher dose of gamma irradiation than that used for sterilization has been reported to increase the wear resistance of UHMWPE. Gamma radiation is also known to induce oxidation involving free radicals in this material, resulting in changes in its mechanical properties. Using the small-punch test, Kurtz et al. [16] reported slight increases in the ultimate characteristics and a failure to work immediately after 20 kGy of gamma irradiation. Deng et al. [13] examined the effect of post-irradiation aging over a period of 5.5 years on the structural and mechanical properties of UHMPWE, which was irradiated at 25 kGy in air, nitrogen, acetylene and a vacuum. The modulus and strength determined under tension or three-point bending increased after gamma irradiation in air for at least 1-year post-irradiation compared with the control results. Deng et al. attributed the increase in the crystallinity of the polymer to its altered mechanical properties. Lewis et al. [6] reported that gamma irradiation at a dose of 50 kGy led to a significant reduction in the tensile and compressive creep properties. McKellop et al. [9] reported a slight increase in yield strength, and decreases in ultimate strength and elongation to failure, as a result of a radiation dose of 45 kGy under static tension. Gillis et al. [2] observed no significant changes in tensile modulus and yield stress with either 25 or 50 kGy dose of gamma irradiation in air, although they did not provide control data. These conflicting results do not indicate a consensus on the effects of low-gamma irradiation on the mechanical properties of UHMWPE. Moreover, these findings have certain limitations when they are applied to clinical situations in which UHMWPE components are subjected to dynamic loads.

To date, a few studies have attempted to characterize the dynamic behavior of unirradiated and gamma-irradiated UHMWPE. Pendulum-type impact testing using the Izod machine has been used to determine the impact strength [9,19]. The Izod impact test measures the energy that is consumed when fracturing a notched specimen, which allows us to compare relative impact resistance to failure. However, as it is difficult to translate the measured energy into stress and strain parameters, the Izod test provides less effective data for the constitutive modeling of the material. The influence of the strain rate on the elastic modulus and yield strength under compression was investigated on virgin and highly crosslinked UHMWPEs at strain rates ranging from 0.02 to 0.10 s^{-1} [17]. The viscoelastic nature of UMWPE can be derived from dynamic mechanical analysis (DMA) and dynamic nanoindentation testing [12]. These methods are capable of determining the storage and loss moduli, based on the assumption that the material that is being tested behaves as a linear viscoelastic solid; they are therefore limited when evaluating plastic and strength behaviors.

We have previously shown the applicability of the split-Hopkinson pressure-bar (SHPB) impact compressive test to UHMWPE [11]. The SHPB method, which was pioneered by Kolsky in 1949 [8], has been widely applied to various kinds of materials, including biological tissues [20]. Compared with other impact-testing methods, the SHPB technique has the advantage of evaluating the dynamic stress–strain relation, which can provide effective data for the development of a dynamic constitutive model that accounts for plastic and strength behaviors.

The purpose of the present study was to determine the effects of strain rate and gamma irradiation on the mechanical properties of UHMWPE. Conventional quasi-static compression tests and impact

compression tests using the SHPB technique were conducted on both unirradiated and gamma-irradiated UHMWPEs, in order to examine the stress–strain relations over a wide range of strain rates.

2. Materials and methods

2.1. Specimen preparation

Thirty cylindrical specimens of 8 mm length and diameter were fabricated from compression-molded GUR 1020. Ten of these specimens were gamma irradiated in nitrogen at a dose of 30 kGy and another 10 specimens were gamma irradiated in air at a dose of 29 kGy. No post-irradiation thermal treatment was performed. The remaining 10 specimens were not irradiated. The unirradiated specimens and those that were irradiated in air were stored in laboratory air for 3 months until the mechanical testing was performed. The specimens that were irradiated in nitrogen were packed securely into an aluminum bag with nitrogen; mechanical testing was carried out after 1 month of storage.

2.2. Impact compressive testing using the SHPB technique

The SHPB apparatus consisted of two elastic pressure bars of 2000 mm length and 10 mm diameter (input and output bars), and a striker bar of 700 mm length and 10 mm diameter (Fig. 1). All three bars were made from high-strength steel rods. After a specimen was placed between the input and output bars, the striker bar was launched to one end of the input bar. The impact speed of the striker bar, as measured using a laser counter, was 2.8 m/s. A compressive-stress pulse generated by this impingement traveled through the input bar, the specimen and the output bar. The incident and transmitted stress waves were detected by foil strain gages that were bonded onto the input and output bars. The signals that were detected were amplified and then recorded using a digital-storage oscilloscope. According to the one-dimensional elastic stress wave-propagation theory, the nominal strain rate ($\dot{\varepsilon}_N$), nominal strain (ε_N) and nominal stress (σ_N) of the specimen were obtained by the following equations [15],

$$\dot{\varepsilon}_N = \frac{2}{\rho_0 c_0 \ell}(\sigma_I - \sigma_T), \tag{1}$$
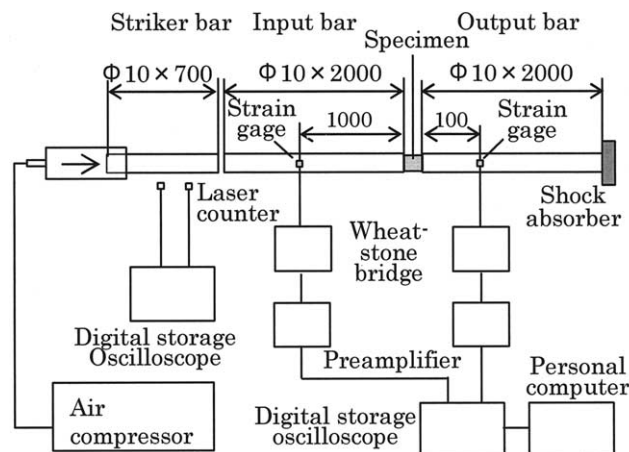

Fig. 1. Schematic drawing of the split-Hopkinson pressure-bar apparatus.

$$\varepsilon_N = \int_0^t \dot{\varepsilon}_N dt = \frac{2}{\rho_0 c_0 \ell} \int_0^t (\sigma_I - \sigma_T)dt, \tag{2}$$

$$\sigma_N = \frac{A_0}{A}\sigma_T, \tag{3}$$

where t is the time, c_0, ρ_0 and A_0 are the longitudinal elastic-wave velocity, density and cross-sectional area of the pressure bars, σ_I and σ_T are the incident and transmitted stress waves, and ℓ and A denote the length and cross-sectional area of the specimen. The true strain (ε) and true stress (σ) of the specimen were defined as follows:

$$\varepsilon = \ln(1 + \varepsilon_N), \tag{4}$$

$$\sigma = \sigma_N(1 + \varepsilon_N). \tag{5}$$

There are potential sources of error in the measurements produced using SHPB, because the inertia effect of the specimen, and the frictional restraint between the specimen and the pressure bars, are not taken into account. Also, Eqs (1)–(3) are derived from the one-dimensional theory, despite the fact that the actual wave motion is three-dimensional in the pressure bars. Davies and Hunter [5] related the inertia effect to the length-to-diameter ratio of the specimen. Lindholm [18] indicated that the frictional restraint was also affected by the length-to-diameter ratio, and experimentally showed that stress in the specimen did not change when the length-to-diameter ratio varied from 0.2 to 2.0. In the present study, as the length-to-diameter ratio of the specimen equals unity, the inertia effect and the frictional restraint can be neglected.

In a rod that is subjected to longitudinal impact, because of the three-dimensional particle motions, the speed of the wave propagation depends on the frequency: the higher the frequency, the slower the wave propagates. This phenomenon is known as dispersion and results in distortion of the wave profile that becomes more notable as the distance traveled by the wave increases. In the SHPB test, the pressure bar is not excited by a pure sinusoid, but rather by a pulse that is composed of a range of frequencies. In addition, the incident and transmitted stress waves are usually measured by strain gages that are placed apart from the ends of the respective pressure bars, to avoid interference from reflective waves. Equations (1)–(3) assume that stress waves travel in the pressure bars with no dispersion; thus, stress waves measured at the position of the strain gages must be identical to those at their interfaces with the specimen. Follansbee et al. [15] revealed that if the ratio of the bar radius to the wavelength is less than 0.01, the effect of dispersion could be negligible. In the present study, as the minimal wavelength is twice as large as the length of the striker bar, 1400 mm, and the radius of the pressure bars is 5 mm, the ratio of the bar radius to the wavelength is less than 0.004.

The accuracy of the strain calculated from Eq. (2) can be checked directly by comparing the calculated value with the strain measured using a strain gage attached to a specimen. Here, the difference observed was within 5%. All tests were conducted at room temperature (about 20°C).

2.3. Quasi-static compressive testing

Quasi-static compressive testing was conducted using a servo-hydraulic load frame (858 Mini-Bionix® II, MTS, Eden Prairie, MN) at a deformation rate of 10^{-2} mm/sec. The nominal stress and true strain relations were calculated from the load-deformation record, and the true stress and true strain were defined according to Eqs (4) and (5). All tests were conducted at room temperature (about 20°C).

2.4. Power-law model fitting

To examine the effect of strain rate on the compressive behavior of UHMWPE, the compressive properties that were determined using the impact and quasi-static tests were fitted to a power-law model,

$$C\dot{\varepsilon}_N^m, \tag{6}$$

where C is a constant and m is the strain rate-sensitivity coefficient. Values of m were compared with those reported by Kurtz et al. [17].

2.5. Statistical analysis

One-way analysis of variance (ANOVA) and the posthoc Bonferroni–Dunn test were performed to examine statistical differences in the compressive properties using the Statview program (SAS Institute, Cary, NC).

3. Results

Figure 2 shows the representative true stress–time and true strain–time relations, which were obtained by SHPB testing for an unirradiated specimen. The difference in peak time between the true stress and true strain was due to the viscosity of UHMWPE. From this result, the strain rate was found to be approximately 260 s^{-1}. The true stress–strain relations are shown in Fig. 3 for unirradiated and gamma-irradiated UHMWPE specimens under impact and quasi-static loading. Each relation was relatively linear up to about 2% strain and the gradient eventually decreased with increasing strain. The strain rate averaged over the linear part was 0.0004 s^{-1} for quasi-static compression. The stress–strain relation below 2% strain was approximated by a straight line in order to determine the Young's modulus. The entire stress–strain curve was then fitted to a cubic polynomial. The intersection of the polynomial and the line having the slope of the Young's modulus and passing the horizontal axis at 0.5% strain was defined as the 0.5% yield stress. The mean values and standard deviations of the mechanical properties, and significant differences due to the strain rate and gamma irradiation, are presented in Tables 1–3.
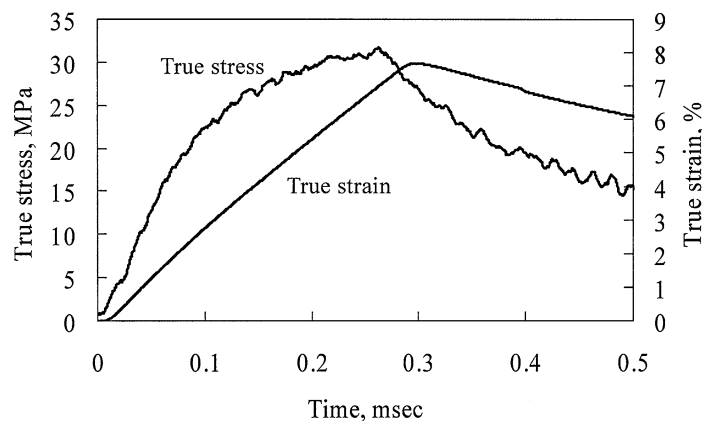

Fig. 2. Representative true stress–time and true strain–time relations for unirradiated UHMWPE.
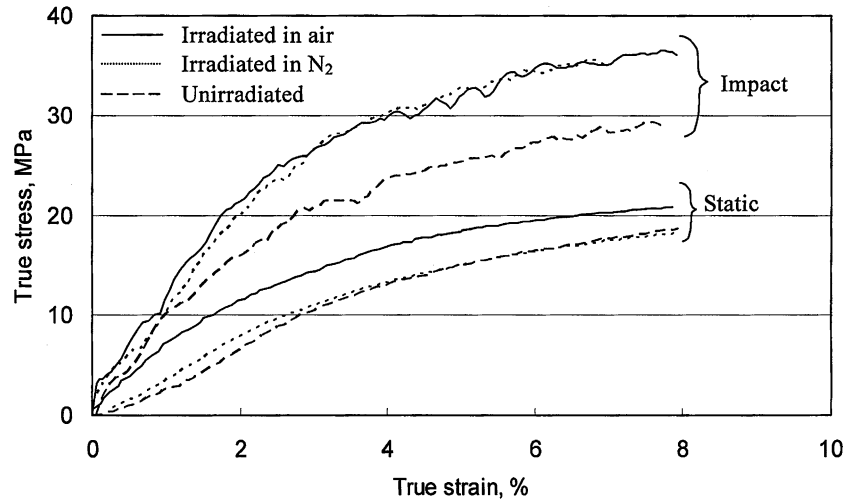
Fig. 3. Representative true stress–strain curves for each UHMWPE specimen.

Table 1

Means and standard deviations for the compressive properties

	Young's modulus, GPa		0.5% yield stress, MPa	
	static	impact	static	impact
Unirradiated	0.435 ± 0.02	0.871 ± 0.026	12.6 ± 0.91	21.3 ± 2.07
Irradiated in N_2	0.410 ± 0.03	0.930 ± 0.020	12.6 ± 0.61	25.6 ± 1.94
Irradiated in air	0.641 ± 0.09	0.981 ± 0.047	11.9 ± 0.98	25.4 ± 1.94

Table 2

Summary of p values for differences in the means of the Young's modulus

	U (static)	N (static)	A (static)	U (impact)	N (impact)	A (impact)
U (static)		0.41	<0.0001	<0.0001	<0.0001	<0.0001
N (static)	–		<0.0001	<0.0001	<0.0001	<0.0001
A (static)	–	–		<0.0001	<0.0001	<0.0001
U (impact)	–	–	–		0.07	0.0011
N (impact)	–	–	–	–		0.08
A (impact)	–	–	–	–	–	

A: Irradiated in air, N: Irradiated in N_2, U: Unirradiated.

A rise of the strain rate by a factor of 10^6 increased the Young's modulus and the 0.5% yield stress drastically for each of the UHMWPE samples. Under impact compression, gamma irradiation in nitrogen or in air increased the Young's modulus and the 0.5% yield stress. By contrast, under static compression, gamma irradiation in nitrogen had no effect on either the Young's modulus or the 0.5% yield stress. Gamma irradiation in air increased only the Young's modulus.

The power-law model was fitted to the relations between the strain rate and the Young's modulus and the 0.5% yield stress. The values of the strain rate-sensitivity coefficient (Table 4) were similar to those reported by Kurtz et al. [17], which ranged between 0.01 and 0.03 for the elastic modulus, and between 0.02 and 0.09 for the 0.2% offset yield strength.

Table 3

Summary of p values for differences in the means of the 0.5% yield stress

	U (static)	N (static)	A (static)	U (impact)	N (impact)	A (impact)
U (static)		0.99	0.53	<0.0001	<0.0001	<0.0001
N (static)	–		0.52	<0.0001	<0.0001	<0.0001
A (static)	–	–		<0.0001	<0.0001	<0.0001
U (impact)	–	–	–		0.0004	0.0007
N (impact)	–	–	–	–		0.82
A (impact)	–	–	–	–	–	

A: Irradiated in air, N: Irradiated in N_2, U: Unirradiated.

Table 4

Values of the strain-rate sensitivity coefficient (m)

	Young's modulus	0.5% yield stress
Unirradiated	0.03	0.05
Irradiated in N_2	0.06	0.05
Irradiated in air	0.05	0.04

4. Discussion

We showed that the Young's modulus and the 0.5% yield stress significantly increased with a rise in the strain rate for both unirradiated and gamma-irradiated UHMWPE specimens. Our data were similar to those reported by Kurtz et al. [17]. In order to study the viscoelastic properties of UHMWPE, Park et al. [12] determined the storage and loss moduli of UHMWPE that was crosslinked by different methods under cyclic loads of up to 5 Hz, using the nanoindentation technique. However, as their indentation depth was less than 1 μm, the two moduli represented the surface properties of the material rather than its bulk properties, which were the focus of the present study. Elastic viscoplastic constitutive models [4,10] were also validated for repetitive loading, although the rates of loading were considerably smaller than those of the present study.

Recent finite element analyses indicated that peak-contact stresses occurring on a tibial polyethylene insert exceeded 20 MPa during a standard gait cycle [1,14], and exceeded 40 MPa during an abnormal gait cycle, assuming malpositioned knee replacement [14]. However, although the strain rates that are experienced during a single gait cycle are not fully understood for a tibial insert, no account was taken of the contribution of the strain rate to the material behavior of UHMWPE. As the strain rates tested here, between 0.0004 and 260 s^{-1}, certainly cover the range during a gait cycle, the present results suggest that the values of plastic strain, as well as the area where the plastic strain distributes under dynamic loads, are smaller than those predicted based on a rate-independent material model for UHMWPE. Consequently, our findings will help to optimize the component design.

After gamma irradiation in air, the Young's modulus significantly increased under both quasi-static and impact compressive loads, whereas the 0.5% yield stress increased only under impact compression. Gamma irradiation in nitrogen increased the Young's modulus and the 0.5% yield stress only under impact compression. The changes in the mechanical properties are probably due to the increase in the crystallinity of UHMWPE that is induced by gamma irradiation, as indicated by Deng et al. [13]. However, McKellop et al. [9] revealed depreciation in the impact strength determined using Izod testing after a radiation dose of 45 kGy, and also showed an increase in the crystallinity of UHMWPE after gamma irradiation. Although the present results support Deng's report, an extensive study taking into account

the change in polymer structure due to storage or aging will be necessary to reach a consensus on this issue.

The present results raise the question of whether the property change obtained here is a mechanical deterioration. The dynamic load-transfer mechanism in implanted joints is different from the static mechanism, because stress and strain must be treated as a wave motion. For components made of UMMWPE alone, increases in the Young's modulus and the yield stress are acceptable. However, stiffened UHMWPE components transfer higher dynamic loads to adjacent materials. This might accelerate the rate of damage of the material and result in a reduction of the longevity of the implant. Consequently, future work should be performed to reveal the dynamic load-transfer mechanism in total joint-replacement systems, using relevant mechanical models for implants as well as biological tissues.

Overall, the present results have the potential to predict elastic and viscoplastic strains more accurately both on and within low-gamma-irradiated UHMWPE components that are subjected to variable conditions *in vivo*. Moreover, SHPB testing can be readily performed on crosslinked UHMWPE in order to reveal its mechanical response to impact compression. However, the present study does have certain limitations. As it evaluated the initial mechanical properties of UHMWPE, possible property changes that are attributable to cyclic loads [3] and long-term aging [13] need to be considered. Also, although the range of strain rates tested was broad, additional data should be collected under intermediate strain rates to clarify the overall strain-rate sensitivity of UHMWPE.

5. Conclusions

The effects of strain rate and low-gamma irradiation were investigated on the compressive properties of UHMWPE. The results showed that a rise of strain rate from 0.0004 to 260 s^{-1} increased the Young's modulus and the 0.5% yield stress for both unirradiated and gamma-irradiated UHMWPE specimens. Gamma-irradiated specimens showed a greater Young's modulus and 0.5% yield stress under impact compression compared with those under static compression. The power-law model was suitable to describe the strain-rate sensitivity in the Young's modulus and the 0.5% yield stress.

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