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Dynamic Compressive Creep of Extruded Ultra-High Molecular Weight Polyethylene

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To estimate the true wear rate of polyethylene acetabular cups used in total hip arthroplasty, the dynamic compressive creep deformation of ultra-high molecular weight polyethylene (UHMWPE) was quantified as a function of time, load amplitude, and radial location of the specimen in the extruded rod stock. These data were also compared with the creep behavior of polyethylene observed under static loading. Total creep strains under dynamic loading were only 64%, 70%, and 61% of the total creep strains under static loading at the same maximum pressures of 2 MPa, 4 MPa, and 8 MPa, respectively. Specimens cut from the periphery of the rod stock demonstrated more creep than those cut from the center when they were compressed in a direction parallel to the extrusion direction (vertical loading), whereas the opposite was observed when specimens were compressed in a direction perpendicular to the extrusion direction (transverse loading). These findings show that creep deformation of UHMWPE depends upon the orientation of the crystalline lamellae.

Key Words : UHMWPE, Dynamic Creep, Total Hip Arthroplasty, Crystalline Lamellar Orientation

1. Introduction

Total hip arthroplasty (THA) of rheumatoid, arthritic, and severely injured hips has provided good pain-free function and independent mobility for many patients. The joint materials used most frequently in THA are ultra-high molecular weight polyethylene (UHMWPE) for the acetabular cup and Co-Cr alloy for the metallic femoral head. In recent years, however, it has become recognized that wear of UHMWPE is an important cause of THA failure. The presence of abundant submicron-sized polyethylene particles strongly suggests that polyethylene has a causative role on bone resorption at the interface between the bone tissue and the prosthesis components (Jasty, 1993). In addition, mechanical failure of THA involves the penetration of the metallic femoral head into the polyethylene acetabular cup during long-term service. This increased penetration depth restricts angular movement (Wroblewski, 1985), and excessive penetration may cause the impingement of the femoral neck on the inside rim of the cup (Isaac et al., 1992). Additionally, the depth of penetration is

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closely correlated with the incidence of cup migration and, in the presence of impingement, joint dislocation (Wroblewski and Siney, 1993).

Although clinical measurements of the average linear wear rate (Rimnac et al., 1988 ; Hernandez et al., 1994 ; Atkinson et al., 1985) of total hip acetabular cups consider the total depth of penetration to be equal to polyethylene cup wear, this dimensional change of the cup is a consequence of both creep (cold flow) and wear. Rose et al. (1980) reported that creep plays an important role ; in their study they noted that up to 70% of the dimensional changes of UHMWPE acetabular cups tested on hip joint simulators were due to creep. Atkinson et al. (1980) reported that creep dominates the early dimensional changes of UHMWPE cups. To accurately assess the true wear rate of polyethylene cups, the amount of creep must be determined under physiological conditions and then subtracted from the clinically measured depth of penetration.

The creep behavior of UHMWPE has been studied by several investigators (Little, 1985 ; Deng et al., 1996 ; Hood et al., 1979 ; Lee and Pienkowski, 1998) who conducted creep tests under static load conditions. However, static load is not an adequate representation of in vivo hip joint loading which typically demonstrates two peak loads per gait (Paul, 1969). Therefore, it is necessary to quantify the creep response of UHMWPE under cyclically fluctuating loads instead of static loads. Additionally, Lee and Pienkowski (1998) reported unexpected anisotropic creep variation as a function of the radial location within a cross-section of extruded rod stock from which specimens were obtained. They speculated that the creep behavior of UHMWPE might be dependent upon the orientation of the crystalline lamellar structure, which varies as a function of radial location in extruded rod stock (Bellare and Cohen, 1996). To validate this hypothesis in the present study, creep tests with two different loads, one in a direction parallel to the plane of the crystalline lamellae, and the other in a direction perpendicular to the plane of the crystalline lamellae, were conducted on specimens from both radial locations (center and periphery).

The objectives of this study were 1) to quantify the compressive creep of dynamically loaded, physiologically maintained UHMWPE as a function of time, peak load amplitude, and radial location of the specimen in the extruded rod stock ; 2) to compare this dynamic creep behavior with the creep behavior observed under static loading ; and 3) to investigate the relationship between creep, direction of loading, and orientation of UHMWPE's crystalline lamellae.

2. Materials and Methods

Extruded un-irradiated GUR 4151HP UHMWPE rod stock (70 mm in diameter, Westlake Plastics, Lenni, PA) was cut into 8 wafers ; each wafer was machined into rectangular specimens (20 mm × 10 mm × 8.8 mm). Two specimens were machined from the center and two from the periphery of each wafer. A total 24 specimens (12 center and 12 periphery) were compressed along the 8.8-mm-thick side, parallel to the direction of extrusion (vertical loading). An additional 8 specimens (4 center and 4 periphery) were compressed along the 10-mm-thick side, perpendicular to the direction of extrusion (transverse loading).

A custom-built creep test machine, operated by a lever arrangement, was used for conducting the dynamic compressive creep tests (Fig. 1). A pair of flat stainless-steel loading platens simultaneously compressed two specimens from the

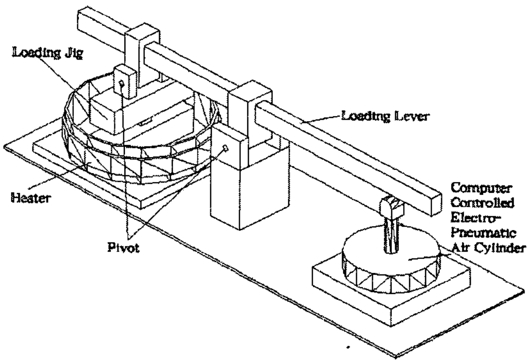

Fig. 1 Schematic diagram of dynamic compressive creep testing apparatus

same radial location of each wafer. The compressive loading was actuated by an air cylinder located at the other end of the lever, and air pressure was regulated by an electro-pneumatic servovalve (Proportion-Air, Inc, McCordsville, IN). Electrical input voltage controlling air pressure was generated by a computer, LabVIEW program, and analog output/input boards (National Instruments, Austin, TX). A miniature compressive loadcell (Omega Engineering, Inc., Stamford, CT) was used to measure the actual applied load and to calibrate the load.

Specimens were immersed in bovine serum (Sigma Chemical Comp., St Louis, MO) diluted with 1% sodium azide solution to retard bacterial growth. The temperature of the bovine serum was maintained at 37℃±0.3℃ by using a thermocouple probe, a negative feedback controller, a solid-state relay, and a heater (Omega Engineering, Inc., Stamford, CT). One of three clinically relevant hip joint pressures (sinusoidal maximum pressures of 2 MPa, 4 MPa, and 8 MPa and minimum pressures of 0.2 MPa, 0.4 MPa, and 0.8 MPa; load ratio of 10 : 1) was dynamically applied to each specimen at 1 Hz for a total duration of 10, 20, 30, 60, 100, 200, 300, 600, 1×10^3, 2×10^3, 3×10^3, 4×10^3, 6×10^3, 8×10^3, and 1×10^4 minutes (6×10^5 loading cycles).

To study the effect of crystalline lamellar orientation on creep deformation, transverse loading under a sinusoidal maximum pressure of 8 MPa and a minimum pressure of 0.8 MPa was applied for up to 4×10^3 minutes. The input electric voltage and the corresponding air pressure for this transverse loading were reset to provide the same level of acting pressure as the vertical loading.

The initial thickness of each specimen was measured with a digital micrometer (Mitutoyo, ±1 μm repeatability) before testing. At the end of each test duration, the specimens were unloaded, cleaned with water, and blotted dry; their thicknesses were then measured at 5 different longitudinal positions, Afterwards, the specimens were replaced into the bovine serum reservoir, and tests were resumed within a constant time interval of 5 minutes. The average of these 5 thickness measurements was subtracted from the initial thickness to quantify the amount of creep. The compressive creep of each specimen was normalized by the initial thickness of the specimen, and this value was called the creep strain. Creep strain data were analyzed as a function of time, pressure, specimen location (center or periphery), and direction of load (parallel or perpendicular to the planes of the crystalline lamellae).

3. Results

The mean dynamic compressive creep strain of the 8 specimens vertically loaded under each sinusoidal pressure varied with time (with the number of loading cycles). This creep strain had a linear relationship ($r^2=0.97$) with the log of time (Fig. 2). Total dynamic compressive creep strain appeared to reach steady state after approximately 4×10^3 minutes, and approximately 88% (90%, 86%, and 89% under each maximum pressure of 2 MPa, 4 MPa, and 8 MPa, respectively) of the total creep strain occurred during the first 10% (10^3 minutes) of the duration of dynamic loading.

The mean dynamic compressive creep strains after 1×10^4 minutes of testing were 3.875×10^{-3}, 8.236×10^{-3}, and 1.637×10^{-2} for the maximum pressures of 2 MPa, 4 MPa, and 8 MPa, respectively. The mean rates of creep strain (slopes of curve fitting in logarithmic time) were 9.098×10^{-4}, 1.996×10^{-3}, and 3.304×10^{-3} (1/log[min.]) for the maximum pressures of 2 MPa, 4 MPa, and 8 MPa, respectively. These creep strains ($2.076\times$

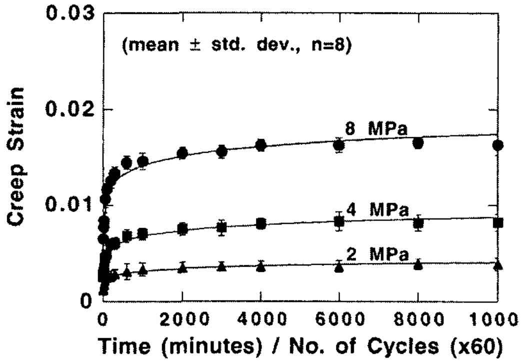

Fig. 2 Mean dynamic compressive creep strain as a function of time for each maximum pressure

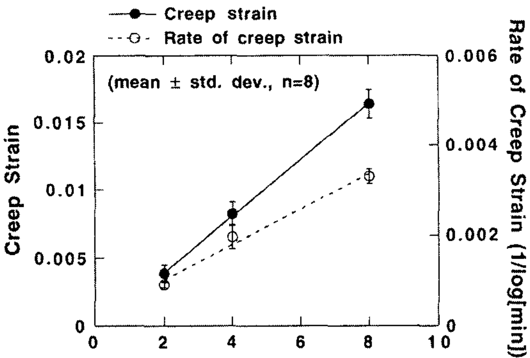

Fig. 3 Variations of mean total creep strain and mean rate of creep strain after 10^4 minutes of test duration as a function of maximum pressure

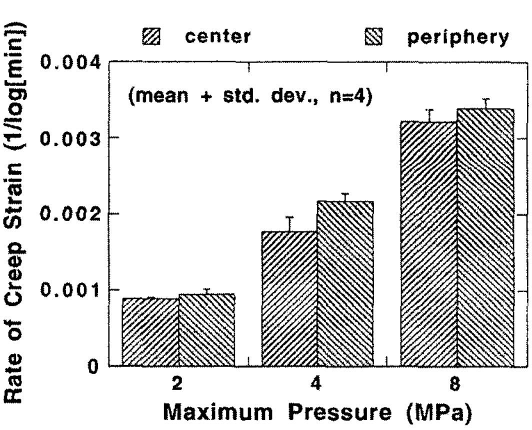

Fig. 4 Variations of mean rate of creep strain as a function of maximum pressure for the specimens from both central and peripheral locations of extruded rod stock

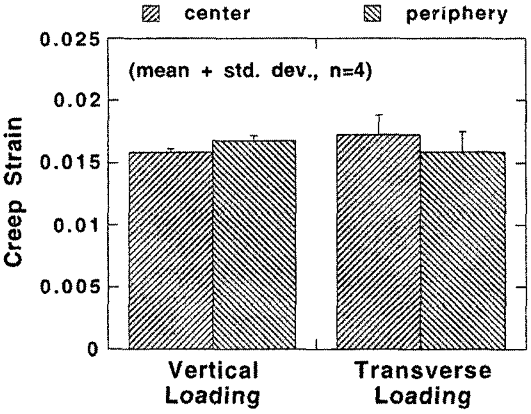

Fig. 5 Differences in creep strain as a function of loading direction

10^{-3}/MPa, $r^2=0.99$) and rates of creep strain (3.897×10^{-4}/log[min.]/MPa, $r^2=0.99$) increased linearly with applied maximum pressure (Fig. 3).

The rate of creep strain varied as a function of the radial location in the extruded rod stock from which the specimens were machined. The specimens machined from the periphery showed 6%, 23%, and 5% greater rates of creep strain than did those from the center of the rod stock for the applied maximum pressures of 2 MPa, 4 MPa, and 8 MPa, respectively (Fig. 4).

The mean creep strain and the mean rate of creep strain of the 8 specimens transversely loaded for as long as 4×10^3 minutes under a maximum pressure of 8 MPa and a minimum pressure of 0.8 MPa were not significantly quantitatively different from those of specimens vertically loaded for the same test duration under the same pressures. However, unlike the vertically loaded specimens, the specimens machined from the center exhibited a 14% greater mean rate of creep strain than did those specimens machined from the periphery of the rod stock. This is an opposite trend of creep deformation as a function of radial location in the extruded rod stock (Fig. 5).

4. Discussion

4.1 Dynamic versus static loading

Compared with static creep results from our previous study (Lee and Pienkowski, 1998), the dynamic creep strain of UHMWPE varied linearly with the log of time and applied maximum pressure, and it reached a steady state after approximately 4×10^3 minutes of each load. These relationships were qualitatively the same as those of static compressive creep results. However, quantitatively there was a big difference. The total dynamic creep strains were only 64%, 70%, and 61% of the total static creep strains observed after 1×10^4 minutes under the pressures of 2 MPa, 4 MPa, and 8 MPa, respectively (Fig. 6). This quantitative difference of creep strain of UHMWPE between dynamic and static loading

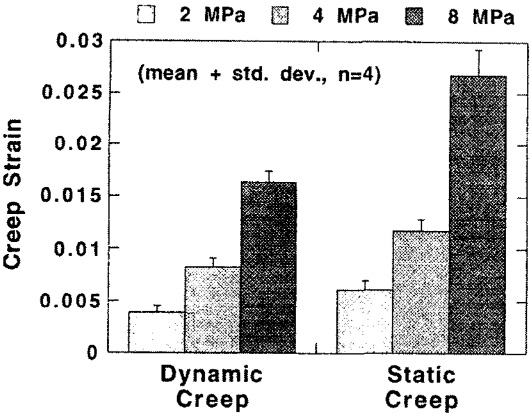

Fig. 6 Differences in creep strain between dynamic and static loading

(the former approximately 2/3 of the latter) may be explained by the viscoelastic recovery that occurs during the unloading phase of a dynamic loading.

Although some studies (Dowling et al., 1978 ; Weightman et al., 1979) suggest that corrosion fatigue under dynamic loading in the presence of synovial fluid affects the in vivo damage of UHMWPE joint components, the results of the present study clearly show that dynamic compressive loading causes less creep deformation of UHMWPE than does static compressive loading. It is not clear whether the accumulation of fatigue damage always accompanies the increase of bulk creep deformation.

Pruitt et al. (1995) demonstrated that: 1) fatigue cracks could be initiated and propagated in UHMWPE subjected to fully compressive cyclic loading, 2) the growth of fatigue cracks was limited, and 3) the cracks saturated without catastrophic failure. The present study did not ascertain whether micro-scale fatigue damage was involved in bulk creep deformation because the test duration of 6×10^5 load cycles is insufficient to simulate long-term in vivo usage, although this number of cycles was sufficient to allow detection of fatigue crack growth in Pruitt's single-edge-notched UHMWPE specimens. According to Pruitt's study, no fatigue cracks are to be expected under the condition of a load ratio of 10 : 1 and a maximum pressure of 8 MPa. It seems that cyclic fatigue has no effect on the accumulation of creep deformation under the present test conditions. However, it is necessary to study fatigue damage in the process of creep deformation in multi-million load cycles at much higher levels of pressure such as the load conditions for the knee.

The average dynamic pressure along the time sequence with a 10 : 1 load ratio of maximum to minimum pressures used in the present experiments was 65% of the maximum pressure. If this average pressure was applied statically, it agreed with the mean value (65%) of the distributed dynamic compressive creep strain : 64%, 70%, and 61%, of static creep strain for each pressure. The same trend was also reported for the creep behaviors of acrylic bone cement (Verdonschot and Huiskes, 1995). It means that a dynamic pressure can be converted to an average static pressure, and, in turn, that dynamic compressive creep can be evaluated from the simple static creep test.

4.2 Effect of semi-crystalline microstructure

The variation in the rate of creep strain as a function of radial location in the rod stock showed that the properties of extruded UHMWPE rod stock were radially anisotropic. Bellare et al. (1996) showed that the orientation of the crystalline lamellae in extruded UHMWPE rod stock gradually changed from an orientation parallel to the direction of extrusion (chain alignment perpendicular to the direction of extrusion) at the center of the rod stock to an orientation perpendicular to the direction of extrusion (chain alignment parallel to the direction of extrusion) near the periphery of the rod stock.

The present results also showed that the radial variation of creep strain is affected by the direction of creep loading. Specimens cut from the periphery of the rod stock demonstrated more creep than did those from the center when they were compressed in a direction parallel to the extrusion direction (vertical loading), whereas the opposite was observed when they were compressed in a direction perpendicular to the extrusion direction (transverse loading).

On the basis of Bellare's observations and the findings of the present study, it appears that creep deformation of UHMWPE depends on the orientation of the crystalline lamellae. UHMWPE deforms more when a load is applied in a direction perpendicular to the plane of crystalline lamellae than when a load is applied in a direction parallel to the plane of crystalline lamellae. It appears that creep deformation is dominant in the amorphous region between the planes of crystalline lamellae.

5. Conclusion

This study quantifies the time-dependent dynamic compressive creep of UHMWPE under physiologic temperature, pressures, and fluid environments. In conjunction with results from the static creep tests, the results of the present study provide useful information to enable estimates of the linear penetration caused by creep of UHMWPE. Thus, the true in vivo wear of the UHMWPE components can be determined by subtracting this creep amount from the total penetration or dimensional change of a UHMWPE acetabular cup.

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