초고분자량 폴리에틸렌 미세구조가 변형과 마모에 미치는 영향
Effect of crystalline lamellar orientation on the creep and wear of ultra-high molecular weight polyethylene

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Abstract

초고분자량 폴리에틸렌 (Ultra-High Molecular Weight Polyethylene) 은 인공관절 라이너에 쓰이는 대표적 생체재료이다. 초고분자량 폴리에틸렌의 변형과 마모에 영향을 주는 인자에 대한 기본적 연구를 위하여 본 연구에서는 미세구조 결정상의 정도와 결정구조 방향성에 따른 초고분자량 폴리에틸렌의 크리프 변형 및 마모 특성의 연구를 행하였다. 압출 제작된 초고분자량 폴리에틸렌 봉 (extruded UHMWPE rod) 단면의 중앙 (center) 부분과 원주 (periphery) 부분으로부터 각각 직사각형 및 원통형의 시편을 제작하여 크리프 실험과 마모 실험을 실시하였다. 원주 시편의 크리프 변형율은 중앙 시편의 크리프 변형율보다 11% 크며 ($p<0.05$), 마모양도 원주 시편이 중앙 시편보다 두 배나 큰 것으로 ($p<0.05$) 관측되었다. 이 결과들로부터 초고분자량 폴리에틸렌의 크리프 변형과 마모가 미세 결정구조 방향성에 영향을 받는 것으로 나타났다.

Keywords: wear, creep, UHMWPE, crystalline lamellar orientation, crystallinity, total joint replacement.

1. Introduction

Ultra-high molecular weight polyethylene (UHMWPE) is the most commonly used bearing material for acetabular liners and tibial plateaus in orthopaedic total joint replacement surgery. Though UHMWPE has the highest abrasion resistance and highest impact strength of any plastic [1], creep and wear of UHMWPE are the serious clinical problems that limit the longevity of joint implants. Excessive creep may lead to gross mechanical failure such as fracture and dislocation [2], and the release of particulate wear debris may induce malign biological response that causes aseptic implant loosening [3].

The degree of creep and wear often depends upon factors unrelated to the polyethylene quality such as patient weight, age, activity level, component thickness, component alignment, conformity, and implantation time, etc. However, the fundamental performance of polyethylene is affected by the properties of polyethylene. Polyethylene-processing determines the microstructure and the relevant properties of UHMWPE even if it is fabricated from the same resin. There are two basic methods of processing of UHMWPE, ram extrusion and compression molding. Both methods evolve from flakes of polyethylene resin being heated under pressure and consolidated into bulk form. It is estimated that eighty percent of the components utilized in orthopaedics have been made from extruded stock, and nowadays, demands for compression molded and machined, or direct compression molded components are increasing.

Recent study with small-angle X-ray scattering analysis [4] showed that the orientation of crystalline lamellae in the ram extruded UHMWPE rod stock varied along the radial direction of cross-section of rod. The crystalline lamellar orientation is parallel to the direction of extrusion at the center of the cross-section of rod, the orientation gradually changes through the mid-section, and near the periphery of the cross-section of rod the crystalline lamellae orient perpendicular to the direction of extrusion. This anisotropic microstructural pattern seems to be caused by the temperature variation during consolidation process. There is an evidence [5] showing that the orientation of molecular chain alignment is crucial for the mechanical properties, especially the ultimate strength and wear resistance of UHMWPE. These reports raise a question if there is a relationship between the crystalline lamellar orientation and in vivo mechanical performance of UHMWPE.

The objective of this study is to investigate the effect of crystalline lamellar orientation in the extruded rod stock on the creep and wear of UHMWPE.

2. Materials And Methods

2-1. Specimen

Three wafers were cut from extruded, un-irradiated, orthopaedic-grade GUR 4150HP UHMWPE rod stock (70 mm diameter, Westlake Plastic, Lenni, PA, USA). For the creep tests a total of 8 (4 center and 4 periphery) rectangular specimens (20 mm long x 10 mm wide x 8.8 mm thick in a direction of extrusion, Fig. 1) were machined from two wafers: two from the center and two from the periphery per each wafer. A total of 8 circular pins (10 mm diameter, 4 center and 4 periphery, Fig. 2) were cored from one wafer. For the wear tests a total of 6 cores (3 center and 3 periphery) were machined to right angle circular cylinders (8 mm long in a direction of extrusion). These flat-ended right angle cylindrical pins guarantee that the contact pressure remains constant during wear testing compared with the flat-ended truncated cylindrical pins which were used by other researchers [6-7] for the small contact area and high contact pressure. The last two cored pins from each radial location of cross-section were used for the measurement of relative crystallinity of UHMWPE.

2-2. Creep Tests

Compressive creep tests were conducted by using custom-built creep testing apparatus operating with a lever arrangement [8]. Two specimens machined from the same radial location of each wafer were simultaneously compressed with a constant pressure of 8 MPa per each specimen by using a pair of flat stainless-steel platens mounted at one end of lever. The opposite end of a lever arrangement was actuated by an air cylinder connected to an electro-pneumatic servo-valve (Proportion Air, McCordsville, IN, USA) that was controlled by a function generation program (LabView, National Instruments, Austin TX, USA). All specimens were tested in a 37℃ bovine serum that was diluted with 1% sodium azide solution at a volume ratio of 2:1 (serum : solution) to retard bacterial growth (Fig. 1.).

The thickness of each rectangular specimen was measured with a digital micrometer (Mytutoyo Corp., Japan, ±0.001 mm repeatability) before testing and after a total loading time interval of 10, 20, 30, 60, 100, 200, 300, 600, 1x10^3, 2x10^3, 3x10^3, 4x10^3, 6x10^3, 8x10^3, and 1x10^4 minutes. At each interval, the load was removed, the specimen was cleaned, and its thickness was measured at five positions. Then the specimen was replaced into the test platen and the test was resumed. The amount of compressive creep was calculated from the difference between the thickness at each interval and the initial thickness of the specimen. The creep strain was calculated by normalizing the creep amount with the initial thickness of each specimen.

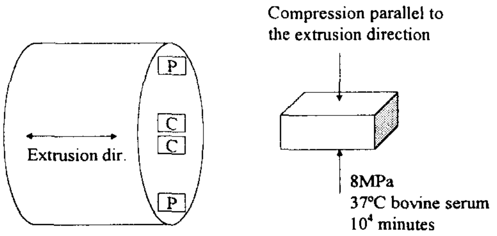

Fig. 1. Schematic diagram of specimen location and creep testing protocol.

2-3. Wear Tests

Wear tests were conducted under UHMWPE pin on a rotating highly-polished stainless steel flat disc (orthopaedic grade 316L, 50.8 mm diameter, R_a = 0.025 μm) in bovine serum diluted with 1% sodium azide solution at a volume ratio of 2:1 (serum : solution) at room temperature. A pin-on-disc wear testing system composed of a lever arrangement and a dead weight exerts a compressive load of 315 N (equivalent to 4 MPa that is about an average contact stress encountered in a hip joint for the normal gait) to each specimen. The disc rotates at a speed of 120 rpm, which is equivalent to the fast normal gait speed, 2 strokes per second, thereby producing a sliding velocity of 125 mm/s at the center of the specimen (Fig. 2.).

All tests were interrupted after every 10 km of sliding distance, the specimen was cleaned with deionized water, dried with a tissue, and weighed with a microbalance (Mettler Instrument Corp., Hightstown, NJ, USA, sensitivity of 0.01 mg). Wear testing was continued for one million revolutions that is equivalent to a total sliding distance of 62.5 km. The amount of wear was determined by weight loss of each specimen, which was corrected for the weight gain that was obtained from a soak control test [9].

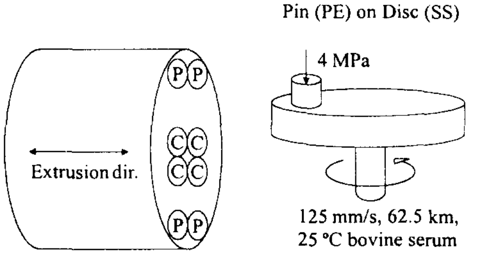

Fig. 2. Schematic diagram of specimen location and wear testing protocol.

2-4. Relative Crystallinity

Relative crystallinity was measured for each center and periphery specimen using differential scanning calorimetry (DSC-7 Series Thermal Analysis System, Perkin Elmer, Danbury, CT, USA). 300 μm-thick slices were microtomed from each specimen, and each slice was cut into a small disc sample with an approximate weight of 10.0 mg and was placed into a sample pan for DSC analysis. Sample pan was heated in the DSC chamber from 30℃ to 180℃ at a rate of 10℃/min, held at 180℃ for 10 minutes, and then cooled to 30℃ at a rate of 10℃/min. The heat of fusion was obtained from the plot of heat flow as a function of temperature. The relative crystallinity was calculated by the heat of fusion for perfectly crystallized polyethylene of 289.74 J/g [10].

3. Results

3-1. Creep

The variation of mean creep strain was plotted in Fig. 3 as a function of time and radial location of specimen. Creep strain increased rapidly in the early period of testing and reached a steady state after about 3-4 x 10^3 minutes.

The mean rate of creep strain (ratio of the creep strain to test duration) of specimens machined from the periphery was 11% greater ($p<0.05$) than that of specimens machined from the center of cross-section of rod stock (Fig. 4).

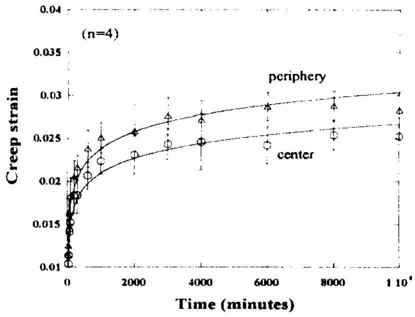

Fig. 3. Variation of the mean compressive creep strain as a function of time for the specimens from both center and periphery locations.

3-2. Wear

The variation of mean weight loss of the center and periphery specimens during wear tests was shown in Fig. 5. After a total sliding of 62.5 km the wear of center specimens was only half ($p<0.05$) that of periphery specimens.

3-3. Relative Crystallinity

There was no difference in the relative crystallinity of specimens machined from the center (mean=47.50±0.74, n=3) and periphery (mean=47.79±0.78, n=3) location of cross-section of the extruded rod stock.

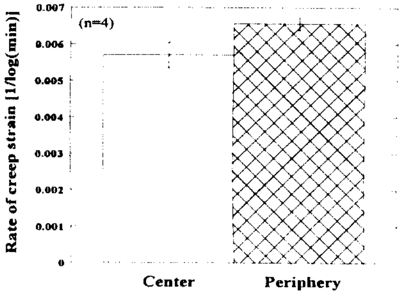

Fig. 4. Variation of the mean rate of creep strain as a function of radial location in the extruded rod stock.

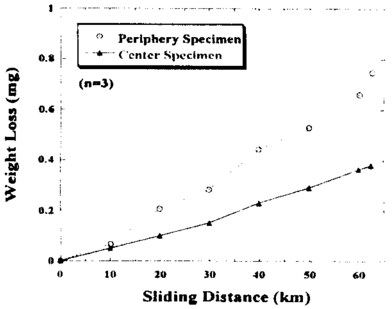

Fig. 5. Variation of the mean weight loss as a function of sliding distance for the specimens from both center and periphery locations.

4. Discussion

The variation of the creep strain and wear of UHMWPE rod stock as a function of radial location of cross-section shows that the properties of extruded UHMWPE rod stock are radially anisotropic. It was perceived that this variation would be due to the irregularity of crystallinity or density in polyethylene. However, the measurement of relative crystallinity of the samples from the same rod showed no variation. Also Evans et al. [11] reported that ram extruded GUR 4150HP rod is extremely consistent in physical and mechanical properties and their variations are much smaller than perception of variability in UHMWPE which may exist because of different resin grades or different testing protocol. Then, what causes the variation of creep and wear along the cross-section of polyethylene rod?

Bellare et al. [4] found that the orientation of the crystalline lamellae in the extruded UHMWPE rod stock gradually changed from an orientation parallel to the direction of extrusion at the center of the rod to an orientation perpendicular to the direction of extrusion near the periphery of the rod.

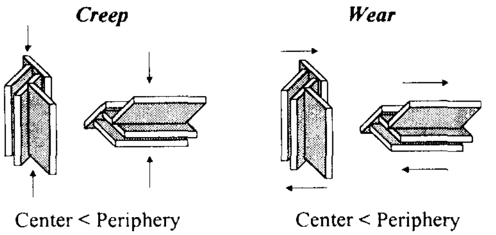

Fig. 6. The characteristic configuration of relationship between a direction of applied load and a orientation of crystalline lamellae in creep and wear of UHMWPE.

On the basis of present findings (come from the UHMWPE rod fabricated by same company using same type of resin) and Bellare's observations, it appears that creep deformation and wear of UHMWPE depends on the orientation of the crystalline lamellae. UHMWPE deforms more when a load is applied in a direction perpendicular to the crystalline lamellae plane than when a load is applied in a direction parallel to the crystalline lamellae plane. For the chain break and debris formation at the sliding contact pair, wear is greater when a shear traction is applied in a direction parallel to the crystalline lamellae plane than when a shear traction is applied in a direction perpendicular to the crystalline lamellar plane (Fig. 6).

This study will be extended to the other UHMWPE specimens manufactured by a different processing method such as compression molded sheet having totally different crystalline lamellar orientation.

5. Conclusion

Combining the Bellare's observation with the present results, creep and wear of UHMWPE vary as a function of the orientation of crystalline lamellae. Creep strain is large when an external load is acting in a direction perpendicular to the crystalline lamellar plane, the amount of wear is great when a shear traction is applied in a direction parallel to the crystalline lamellar plane.

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