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Short-term creep and recovery behavior of medical grade ultra-high molecular weight polyethylene (UHMWPE)

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ABSTRACT

Purpose: In this study, short-term tensile creep and recovery behaviors of medical grade ultra-high molecular weight polyethylene (UHMWPE) were investigated to contribute deformation behaviour of UHMWPE components in knee and hip prosthesis during daily life activities of patients.

Design/methodology/approach: Tensile test specimens were machined from compression molded UHMWPE sheets having commercial brand name: Chirulen 1020 and they were prepared according to ASTM 527-2. The tensile creep tests were performed at constant stress levels of 5, 9, 13, 18 and 21 MPa as long as 1 hour for each test. Then, the specimens were allowed to recover unloaded for 1 hour. Automatic extensometer was used to measure the deformations precisely for each test.

Findings: Results show that creep rate linearly increased with increasing the stress levels. Permanent deformations were observed after recovery. Recovery of the material became difficult with increasing the applied load at intended time interval.

Research limitations/implications: UHMWPE components used in prosthesis have been subjected to complex loading conditions during service life. Polymeric materials show the viscoelastic material properties like strain rate sensitivity, relaxation, creep and recovery at room temperature. Because of the viscoelastic material properties of the UHMWPE, it makes difficult to predict the failure of the UHMWPE components in hip and knee prosthesis. Therefore, deformation behavior of medical grade UHMWPE should be investigated in many different loading conditions.

Practical implications: Medical grade ultra-high molecular weight polyethylene (UHMWPE) have been used commonly in total hip replacements as acetabular cup and in total knee replacements as tibial insert since early 1960s.

Keywords: Medical grade UHMWPE; Tensile creep; Recovery; Viscoelastic material

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BIOMEDICAL AND DENTAL ENGINEERING AND MATERIALS

1. Introduction

UHMWPE have been used as bearing components in total joint replacements since Dr. John Charnley introduced this material in total hip replacement surgery in the early 1960s. Biocompatibility, high toughness, wear resistance and high impact strength properties have made this polymeric material attractive to use in human artificial joints [1,2]. About three millions of total joint replacements surgeries are performed around the world for each year [3]. Unfortunately, revision rates of these procedures are 6% at five years and 12% after ten years [4].

Wear and surface deformation of the UHMWPE components in the prosthesis are defined the reasons for revision of total joint arthroplasty. Kim, et al. [5] have done a prospective study about revisions of total knee arthroplasty and found that most common failure modes required for revision were UHMWPE component wear (45%) followed by infection (26%) and loosening (17%) on the patients under 55 years old. Dalury, et al. [6] recorded reasons for revisions on total knee arthroplasties between 2000-2012 years. The data collected from the patients having mean age of 69 years showed that the most common reasons for revisions were aseptic loosening (23.1%), infection (18.4%), UHMWPE wear (18.1%), instability (17.7%), pain/stiffness (9.3%), osteolysis (4.5%) and malposition/malalignment (2.9%). Springer, et al. [7] reviewed the revision records of total hip arthroplasty between 1986-2005 years. They identified that the most common revision reasons were instability (35%), aseptic loosening (30%), osteolysis and wear (12%), infection (12%), miscellaneous (9%) and periprosthatic fracture (2%).

Daily activities, ages and weights of patients having implants are parameters determining loads acting on hip and knee joints. UHMWPE tibial inserts and acetabular cups are directly subjected to contact forces. Daily activities can be defined as walking, ascending stairs, descending stairs, knee bend, standing up, standing down, one-legged stance and jogging. Previous studies reported that knee joint contact forces occurred 2.2-2.5 times body weight (BW) during walking, 2.4- 2.7 times BW during one legged stance, 2.8-3.5 times BW during ascending and descending stairs in vivo [8-11]. Hip joint contact forces occurred 2.3-2.8 times BW during walking, 2.5-3.8 times BW during ascending and descending stairs in vivo [12,13]. Contact area of tibiofemoral surface in the knee prosthesis is changing between 200-800 mm^2 at different knee flexion angles and in different knee implant designs [14]. Aforementioned studies show that UHMWPE total joint components in the prostheses are subjected to contact stresses that remain below 22.6 MPa yield stress for medical grade UHMWPE Chirulen 1020.

Polymeric materials show the viscoelastic material properties like strain rate sensitivity, relaxation, creep and recovery at room temperature. Because of the viscoelastic material properties of the UHMWPE, it makes difficult to predict the failure of the UHMWPE components in hip and knee prosthesis. Therefore, there have been some studies that investigate creep and recovery behaviour of different forms of medical grade UHMWPE [15-17]. Wear, together with surface deformation in consequence of creep are shortened service life of the UHMWPE total joint components even if the contact stresses are below the yield stress because of the viscoelastic properties of the material. Therefore, we performed the short-term creep and recovery tests at different stress levels below yield stress to contribute deformation behaviour of UHMWPE components in knee and hip prostheses during daily life activities of patients.

2. Material and method

2.1. Material

Medical grade UHMWPE compression molded sheets (Chirulen 1020) with 55 mm thickness was purchased from MediTECH Medical Polymers (Vreden, Germany). Chirulen 1020 compression molded sheets are made from GUR® 1020 premium resins of Celanese Company. These commercial brand is commonly used for knee, hip, shoulder and elbow implants. Chirulen 1020 have the superior physical and mechanical properties when compared to UHMWPE sheets used in industrial applications. Tensile properties of Chirulen 1020 according to ISO 527-2 can be seen in Table 1.

Table 1.
Tensile properties of UHMWPE Chirulen 1020

	Unit	Average value
Tensile stress at yield	MPa	22.2
Tensile stress at break	MPa	59
Elongation percent at break	%	460
Tensile (Young's) modulus: 2 mm thick specimens	MPa	660

2.2. Method

UHMWPE compression moulded sheet having 55 mm thickness was cut in strips with 4 mm thickness by bandsaw machine. Tensile test specimens were punched from the strips by tensile specimen cutter manufactured in dimensions in accordance with ISO 527-2 Type 1B. Preparation of the specimens can be seen in Figure 1.

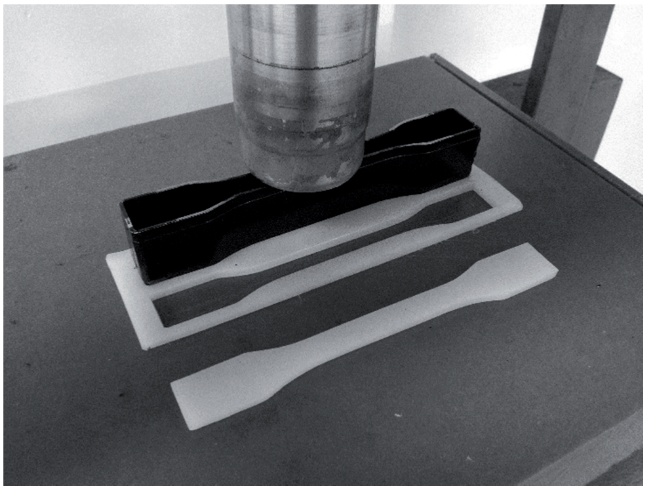

Fig. 1. Tensile specimen cutter and punching the specimens by manual hand press

Tensile creep and recovery tests were performed using a Shimadzu Autograph AG-IC 50 kN with computer controlled universal testing machine at room temperature. 5 kN load cell having high precision of ±0.1% of the indicated test force was assembled to universal testing machine and used for the tests. Strains were measured by Shimadzu SIE-560 automatic extensometer having high precision ±0.5% of indicated value of elongation (Fig. 2). The test data were recorded and processed using the TrapeziumX software provided by Shimadzu.

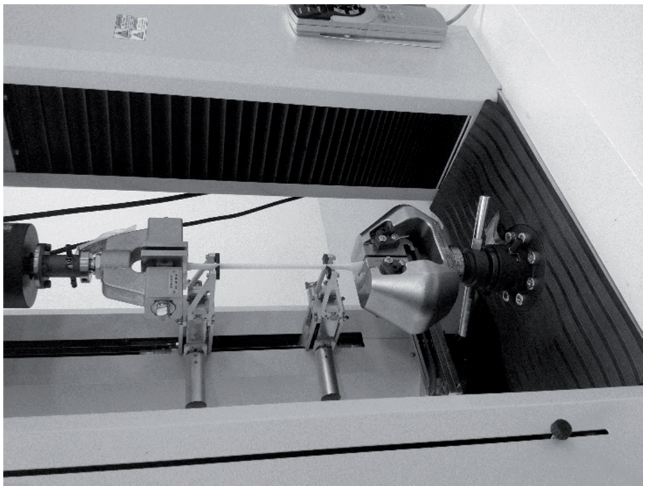

Fig. 2. Test condition and strain measurement by automatic extensometer

The controlled creep and recovery tests which can be adjusted using TrapeziumX software were performed for each specimen at a few steps after the test specimens were mounted in testing grips and extensometer grips. In first step, the specimens were loaded with the loading rate of 100 mm/min up to desired stress levels. In second step, they were hold as long as 1 hour at desired constant stress levels (5, 9, 13, 18 and 21 MPa) for each specimen. In third step, they were unloaded with the unloading rate of 100 mm/min down to 0 N. In the final step, they were allowed to recover as long as 1 hour at 0 N.

Creep is a progressive deformation of a material at constant stress levels. The deformation is a function of time (time-dependent) under constant load applied to specimen. Creep behaviour of thermoplastic polymers is described in Figure 3. Creep behaviour is defined as three regions: Primary, secondary and tertiary creep. The slope of curve decreases rapidly with time in primary creep. Constant strain rates occur and deformation is proportional to time in secondary creep. The slope of curve increases rapidly with time until creep rupture occur in tertiary creep. Increasing load accelerates the deformation and shortens the time to reach rupture. t1, t2 and t3 times state this phenomenon. The material creeps until rupture with sufficient load and time [18,19].

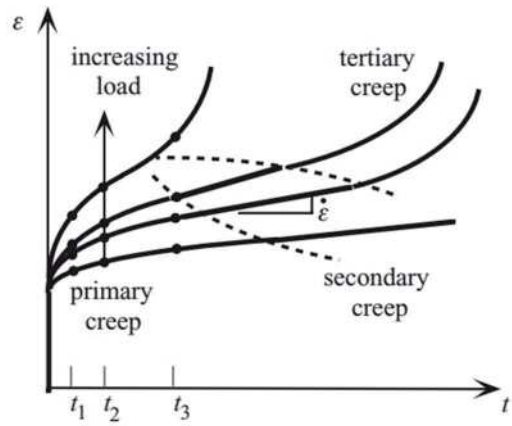

Fig. 3. Creep curve – strain (ε) vs. time (t). Adapted from ([19], p. 5)

3. Results and discussions

Creep and recovery behaviour of UHMWPE Chirulen 1020 for stress levels of 5, 9, 13, 18, 21 MPa are shown in Figure 4 and Figure 5. After loading for each stress levels, instantaneous deformation firstly occurs including elastic and inelastic part. The next step, strain increases depending on the magnitude of the applied stress as long as the constant load is maintained. When the load is removed at the end of 1-hour, the elastic deformation instantly is recovered and then slow recovery is observed with time. At the end of 1-hour recovery, permanent deformations remain depending on the magnitude of the applied load. Accumulated creep strains and residual strains of recovery for each stress levels at the end of 1-hour are shown in Figure 6 and Figure 7. The results show that total creep deformation increases with increasing the applied load. However, recovery of the tested material becomes difficult with increasing the applied load at intended time interval.

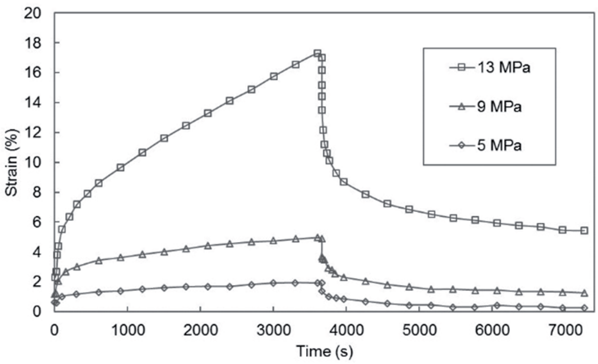

Fig. 4. Creep and recovery curves for stress levels of 5, 9 and 13 MPa

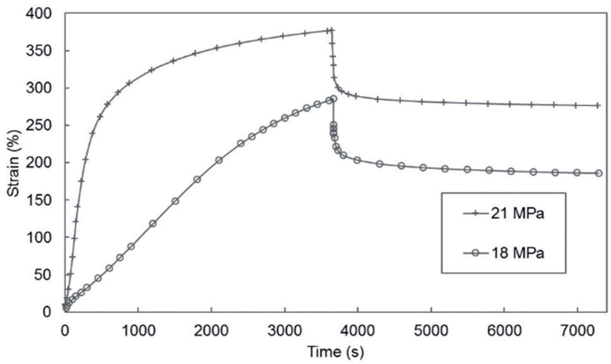

Fig. 5. Creep and recovery curves for stress levels of 18 and 21 MPa

Primary and secondary regions of the creep for stress levels of 5, 9 and 13 MPa can be obviously seen in Fig. 4. Strain rate decreases rapidly in primary creep and then strain rates become constant in secondary creep region. It is difficult to see primary and secondary creep regions of 18 and 21 MPa stress levels in Figure 5. Closer creep deformation view of 13, 18 and 21 MPa stress levels for duration of the first 120 seconds is shown in Figure 8. While the primary and secondary creeps occur at 13 and 18 MPa, tertiary creep can be seen at 21 MPa for duration of the first 120 seconds in Figure 8. Tertiary creep region for 18 MPa stress level occurs slightly in between 500- 1200 seconds and it can be seen in Figure 5.

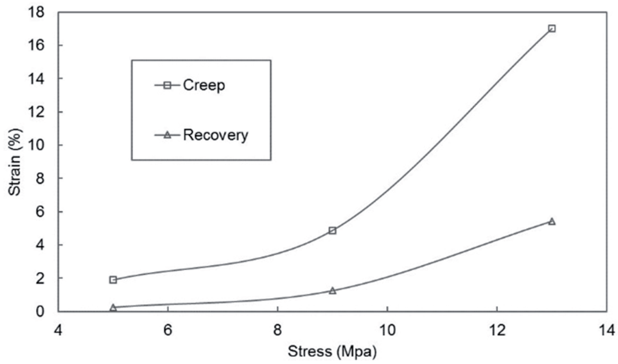

Fig. 6. Accumulated creep deformations at 1-hour of loading for stress levels of 5, 9, 13 MPa and permanent deformations after recovery through 1-hour

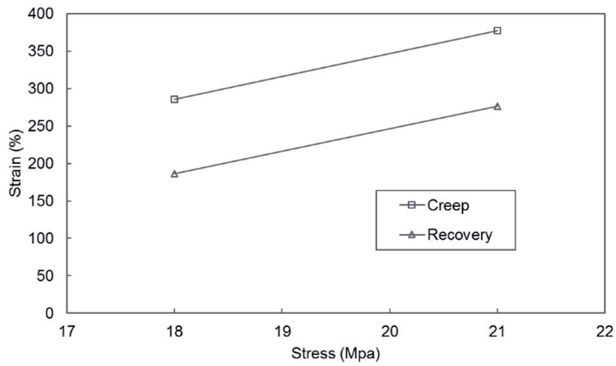

Fig. 7. Accumulated creep deformations at 1-hour of loading for stress levels of 18 and 21 MPa and permanent deformations after recovery through 1-hour

Deformations are proportional to time in secondary creep region. Therefore, slope of the curve at the stage of the secondary creep gives the creep rate ($\dot{\varepsilon}$) in Figure 3. Logarithmic scale of creep rate for each stress levels is shown in Figure 9.

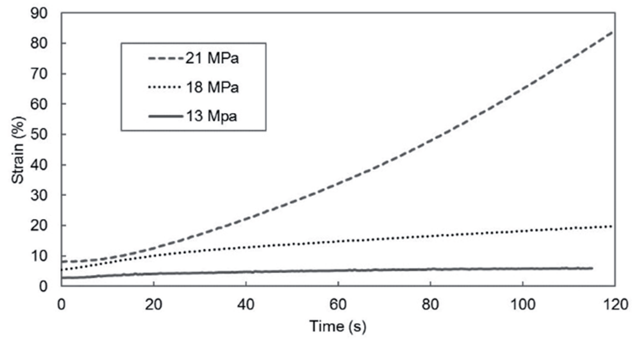

Fig. 8. Closer view of creep deformations at first 120 s of loading for stress levels of 13, 18, 21 MPa

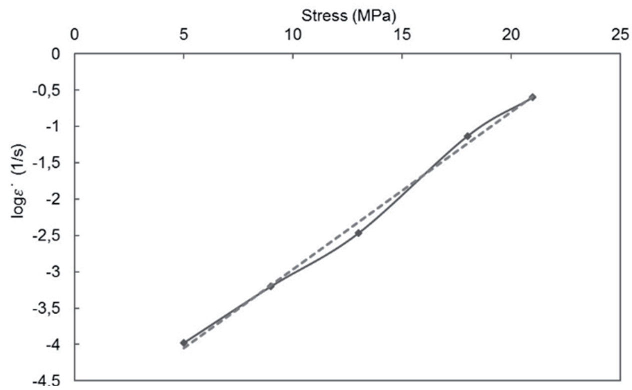

Fig. 9. Logarithmic scale of creep rate ($\dot{\varepsilon}$) versus stress

4. Conclusions

The short creep and recovery behaviour of Chirulen 1020 UHMWPE was presented in this study. The creep results show that creep rate increases almost linearly with increasing the applied load. The recovery results show that recovery of the tested material becomes difficult with increasing the applied load at intended time interval. Accumulated creep strains and residual strains of recovery were increased nonlinearly with increased stress levels. The all short creep and recovery test results contribute to the deformation behaviour of UHMWPE components in knee and hip prosthesis during daily life activities of patients.

Acknowledgements

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References

[1] G. Chakrabarty, M. Vashishtha, D. Leeder, Polyethylene in knee arthroplasty, Journal of Clinical Orthopaedics and Trauma 6 (2015) 108-12.

[2] M.K. Musib, A Review of the History and Role of UHMWPE as A Component in Total Joint Replacements, International Journal of Biological Engineering 1 (2012) 6-10.

[3] S.M. Kurtz, UHMWPE Biomaterials Handbook: Ultra High Molecular Weight Polyethylene in Total Joint Replacement and Medical Devices, Elsevier Science, 2015.

[4] G. Labek, M. Thaler, W. Janda, M. Agreiter, B. Stöckl, Revision rates after total joint replacement, Cumulative Results from Worldwide Joint Register Datasets 93-B (2011) 293-297.

[5] K.T. Kim, S. Lee, D.O. Ko, B.S. Seo, W.S. Jung, B.K. Chang, Causes of failure after total knee arthroplasty in osteoarthritis patients 55 years of age or younger, Knee Surgery & Related Research 26 (2014) 13-19.

[6] D.F. Dalury, D.L. Pomeroy, R.S. Gorab, M.J. Adams, Why are total knee arthroplasties being revised?, Journal of Arthroplasty 28 (2013) 120-121.

[7] B.D. Springer, T.K. Fehring, W.L. Griffin, S.M. Odum, J.L. Masonis, Why revision total hip arthroplasty fails, Clinical Orthopaedics and Related Research 467 (2009) 166-173.

[8] G. Bergmann, A. Bender, F. Graichen, J. Dymke, A. Rohlmann, A. Trepczynski, et al., Standardized loads acting in knee implants, PLoS One 9 (2014) e86035.

[9] D.D. D'Lima, N. Steklov, B.J. Fregly, S.A. Banks, C.W. Colwell, Jr., In vivo contact stresses during activities of daily living after knee arthroplasty, Journal of Orthopaedic Research 26 (2008) 1549-1555.

[10] A. Mundermann, C.O. Dyrby, D.D. D'Lima, C.W. Colwell, Jr., T.P. Andriacchi, In vivo knee loading characteristics during activities of daily living as measured by an instrumented total knee replacement, Journal of Orthopaedic Research 26 (2008) 1167-1172.

[11] S.J.G. Taylor, P.S. Walker, J.S. Perry, S.R. Cannon, R. Woledge, The forces in the distal femur and the knee during walking and other activities measured by telemetry, The Journal of Arthroplasty 13 (1998) 428-437.

[12] G. Bergmann, A. Bender, J. Dymke, G. Duda, P. Damm, Standardized Loads Acting in Hip Implants, PLoS One 11 (2016) e0155612.

[13] G. Bergmann, G. Deuretzbacher, M. Heller, F. Graichen, A. Rohlmann, J. Strauss, et al., Hip contact

forces and gait patterns from routine activities, Journal of Biomechanics 34 (2001) 859-871.
[14] K. Shiramizu, F. Vizesi, W. Bruce, S. Herrmann, W. R. Walsh, Tibiofemoral contact areas and pressures in six high flexion knees, International Orthopaedics 33 (2009) 403-406.
[15] M. Deng, R.A. Latour, A.A. Ogale, S.W. Shalaby, Study of creep behavior of ultra-high-molecular-weight polyethylene systems, Journal of Biomedical Materials Research 40 (1998) 214-223.
[16] K.-Y. Lee, D. Pienkowski, Compressive creep characteristics of extruded ultrahigh-molecular-weight polyethylene, Journal of Biomedical Materials Research 39 (1998) 261-265.
[17] A.H.I. Mourad, H. Fouad, R. Elleithy, Impact of some environmental conditions on the tensile, creep-recovery, relaxation, melting and crystallinity behaviour of UHMWPE-GUR 410-medical grade, Materials & Design 30 (2009) 4112-4119.
[18] H. F. Brinson and L. C. Brinson, Polymer Engineering Science and Viscoelasticity, An Introduction,Springer US, 2008.
[19] R. Lakes, Viscoelastic Materials, Cambridge University Press, 2009.