Available online at www.sciencedirect.com
SCIENCE @ DIRECT®
Biomaterials 24 (2003) 3193–3199
Biomaterials
www.elsevier.com/locate/biomaterials

Effect of consolidation on adhesive and abrasive wear of ultra high molecular weight polyethylene

Rizwan M. Gul[a], Frederick J. McGarry[b], Charles R. Bragdon[c], Orhun K. Muratoglu[c,*], William H. Harris[c]

[a] Faculty of Metallurgy and Materials Engineering, GIK Institute of Engineering Sciences and Technology, Topi 23460, District Swabi, Pakistan
[b] Department of Materials Science and Engineering, Massachusetts Institute of Technology, Cambridge, MA, USA
[c] Orthopaedic Biomechanics and Biomaterials Laboratory, Massachusetts General Hospital, GRJ 1206, 55 Fruit Street Jackson, Boston, MA 02114, USA

Received 25 November 2002; accepted 9 March 2003

Abstract

Total hip replacement (THR) is widely performed to recover hip joint functions lost by trauma or disease and to relieve pain. The major cause of failure in THR is the wear of the ultra high molecular weight polyethylene (UHMWPE) component. The dominant wear mechanism in THR occurs through adhesion and abrasion. While poor consolidation of UHMWPE is known to increase the incidence of a different damage mode, delamination, which is the dominant wear mechanism in tibial inserts but uncommon in THR, the effect of consolidation on adhesive and abrasive wear of UHMWPE is not clear. In this study UHMWPE resin was subjected to hot isostatic pressing under a pressure of 138 MPa at different temperatures (210°C, 250°C, and 300°C) to achieve varying degrees of consolidation. The extent of consolidation was determined by optical microscopy using thin sections, and by scanning electron microscopy using cryofractured and solvent etched specimens. Wear behavior of the samples with varying degree of consolidation was determined using a bi-directional pin-on-disc machine simulating conditions in a hip joint. Increasing the processing temperature decreased the incidence of fusion defects and particle boundaries reflecting the powder flakes of the virgin resin, improving the consolidation. However, the bi-directional pin-on-disc wear rate did not change with the processing temperature, indicating that adhesive and abrasive wear is independent of the extent of consolidation in the range of parameters studied here.

Keywords: Ultra high molecular weight polyethylene; Wear; Total joint replacement; Processing temperature; Consolidation; Fusion defects

1. Introduction

Total hip and total knee arthroplasty are widely performed to recover joint functions when lost by trauma or disease and to relieve pain. Ultra high molecular weight polyethylene (UHMWPE) has been the material of choice for the fabrication of one side of the load bearing surface used in both total hip and total knee replacements. Damage to UHMWPE in vivo is an important factor that adversely affects the long-term performance of the reconstructed joint. Two primary damage mechanisms, namely delamination and adhesive/abrasive wear, are commonly observed in surgically explanted UHMWPE components. Delamination is initiated by sub-surface cracks, which propagate to the articulating surface, leading to the removal of relatively large (>0.5 mm) flake-like debris. Adhesive/abrasive wear generally follows the orientation and strain hardening of the implant surface and subsequent implant motion results in the removal of small wear debris, usually on the order of a few micrometers or less in size. Abrasive wear occurs through the rubbing action of the hard asperities on the surface of the femoral component. It is also accentuated by hard third body particles, such as bone chips or bone cement particles, within the articulation. Abrasive wear progresses by the cutting and removal of the polyethylene articular surface.

Peri-prosthetic osteolysis secondary to particulate debris is the major cause of long-term failure in total

*Corresponding author. Tel.: +1-617-726-3869; fax: +1-617-726-3883.
E-mail address: omuratoglu@partners.org (O.K. Muratoglu).

0142-9612/03/$ - see front matter © 2003 Elsevier Science Ltd. All rights reserved.
doi:10.1016/S0142-9612(03)00165-0

Table 1
Wear rate (mg/million cycles) of the test samples

Sample ID	Resin type	Temperature (°C) of hot isostatic pressing	Wear rate (mg/million cycles)
Ram Extruded	GUR 415	Not applicable	9.88 (±0.48)
H1-GUR	GUR 405	210	7.87 (±0.05)
H2-GUR	GUR 405	250	8.75 (±0.54)
H3-GUR	GUR 405	300	9.36 (±0.27)
H1-1900	Himont 1900	210	9.87 (±0.57)
H2-1900	Himont 1900	250	9.10 (±0.80)
H3-1900	Himont 1900	300	8.68 (±1.06)

hip replacements, leading to component loosening and in many cases resulting in revision surgery. The particulate debris is predominantly generated by the adhesive/abrasive wear of UHMWPE articular surface [1–4]. Therefore, research efforts have been concentrated on understanding the structure-property relations pertaining to UHMWPE and improving both forms of its damage resistance.

UHMWPE is synthesized through a Zieglar-Natta catalyst in the form of resin flakes [5]. The average molecular weight is typically 4–6 million grams per mole, which results in a high entanglement density and high melt viscosity. As a result, large-scale melt processing of the resin is not possible. Most UHMWPE articles are machined from consolidated stock. The consolidation is commonly carried out by either ram extrusion or compression molding, both of which rely on sintering the resin flakes at an elevated temperature and pressure. Consolidation fuses the resin flakes but generates distinct boundaries between the flakes [6]. The high entanglement density of the UHMWPE molecules is thought to prevent self-diffusion and result in the formation of these flake boundaries. In addition to the ubiquitous flake boundaries, fusion defects are found in the consolidated UHMWPE as well [7–10]. Fusion defects have been attributed to the agglomerated calcium stearate additive and poor consolidation [6].

It has been proposed that the in vivo UHMWPE damage may be a function of the degree of consolidation, and should decrease with the elimination of fusion defects or flake boundaries. There is clinical evidence for an increase in delamination type wear in tibial knee inserts with decreasing degree of consolidation. For instance, Mayor et al. [11] found a statistically significant correlation between fusion defects and delamination and cracking in a UHMWPE tibial knee insert used in total knee arthroplasty. Landy and Walker [12] also related the occurrence of delamination type wear in a knee joint to fusion defects in the material. Similarly, Walker et al. [13] and Blunn et al. [14] proposed that fusion defects serve as initiation sites for cracks, which under repeated loading results in the release of wear particles. While the detrimental effect of poor consolidation on the delamination resistance of UHMWPE is well documented, its effects on adhesive and abrasive wear are not known.

The aim of the present study was to investigate the adhesive and abrasive wear behavior of UHMWPE with varying degrees of consolidation. Two different types of UHMWPE resins, namely Himont 1900 and GUR 405, were included in the present investigations. These resins are surgical grade resins used in the fabrication of both tibial inserts and acetabular liners. The degree of consolidation was varied by changing the processing temperature during hot isostatic pressing. The wear tests were carried out using a bi-directional pin-on-disk machine capable of producing adhesive and abrasive wear mechanisms [15] (Table 1).

2. Methods and materials

Two types of UHMWPE resins were studied, namely GUR 405 (Hoechst Celanese, League city, TX) and Himont 1900 (Himont USA, Wilmington, DE), which were obtained in their powder form. The Himont 1900 resin contained no added calcium stearate. The resins were stored for less than 5 months prior to consolidation and testing. The virgin resins were consolidated by hot isostatic pressing at different temperatures to achieve varying degrees of consolidation. Hot isostatic pressing involves the application of hydrostatic gas pressure at elevated temperatures as opposed to uniaxial force used in ram extrusion and compression molding. The resins were first compacted in the form of a cylinder and subjected to cold isostatic pressing at 276 MPa at room temperature. The compacted specimens were then packaged and hermetically sealed under vacuum. The specimens to be processed at 210°C were enclosed in a laminated foil bag made of Mil-b-131H Class 1 Type 1 sheet, and those specimens to be processed at 250°C and 300°C were enclosed in a thin stainless steel sheet can. The hot isostatic pressing was performed at Industrial Materials Technology, Andover, MA.

The processing temperatures included 210°C (H1), 250°C (H2), and 300°C (H3). Samples of both groups of resins, GUR 405 and Himont 1900, were consolidated at 210°C, 250°C, and 300°C under a hydrostatic pressure of 138 MPa. During hot isostatic pressing the heat soak time and cooling rate were kept constant for all three processing temperatures at 2 h and 3°C/min, respectively. A commercially available ram extruded bar stock (Westlake Plastics, Lenni, PA) processed from GUR 415 resin was also included as a reference material.

Thin sections (20 μm) of the consolidated specimens were prepared by using a sledge microtome. These sections were analyzed using an Olympus BH2 (Olympus Optical Co., Tokyo, Japan) under transmitted polarized light. The presence of fusion defects and sphereulites were noted when present.

To visualize the boundaries of the virgin resin flakes, specimens were fractured after being submerged in liquid nitrogen for 1 h. The cryofractured specimens were gold coated and analyzed using a Stereoscan 240 (Cambridge Instruments, Cambridge, England) scanning electron microscope (SEM). Solvent-etching was used to qualitatively assess the extent of consolidation at the virgin resin flake boundaries as follows. Specimens were mounted in epoxy, polished with SiC paper and alumina powder of 0.05 μm particle size. After cleaning in an ultrasound bath of water, the epoxy mounted specimens were dipped in 98% Decalin at 150°C for 45 s. The etched surfaces were gold coated for SEM analysis.

A bi-directional pin on disc wear testing machine modeling the multidirectional motion of the hip joint was used to characterize the wear behavior of the consolidated specimens [15]. The bi-directional pin-on-disk machine rubbed a UHMWPE pin against a cobalt-chrome disk counterface with implant surface finish (Ra = 0.38 ± 0.005 μin). The rubbing action followed a rectangular path (5 × 10 mm). The tests were conducted with 100% bovine serum (JRH Biosciences, Lenexa, KS) as lubricating medium. A Paul type load curve was used with a peak load of 267 N which resulted in a normal peak contact stress of 4.2 MPa [15]. The test frequency was 2 Hz. The polyethylene pins used for wear testing were cleaned and weighed at the beginning of the test, after 0.5 million cycles and at the end of the test after 1 million cycles. Two pins, 9 mm in diameter and 13 mm in height, of each series of both consolidated resins and the ram extruded GUR 415 bar stock were wear tested. The incremental wear rates measured at two intervals for the samples of each group were used to carry out an ANOVA two-factor with replication analysis. *P*-values less than 0.05 were considered significant.

3. Results

The analysis by optical microscopy confirmed the presence of fusion defects and some unconsolidated flakes in both the reference material (the ram extruded bar stock) and in the GUR 405 resin processed at 210°C. Himont 1900 resin processed at 210°C exhibited relatively fewer number of fusion defects as compared to GUR 405 resin processed at the same temperature. Consolidation improved for both resins as the processing temperature increased to 250°C and 300°C, as was observed with the decrease in the number of fusion defects and unconsolidated flakes.

The Himont 1900 samples processed at 250°C showed clusters of spherulites. The same resin consolidated at 300°C was completely spherulitic as shown in Fig. 1a. None of the GUR 405 samples exhibited spherulites as shown in Fig. 1b.

Fig. 2 shows representative SEM micrographs of the cryofractured surfaces of the materials studied. The reference material and the GUR 405 sample processed at 210°C exhibited a similar appearance on the cryofractured surfaces, a star-burst morphology. The fracture lines that border the star-burst features are thought to coincide with the borders of the powder flakes of the virgin resin. As the processing temperature of GUR 405 resin was increased to 250°C and 300°C, the star-burst pattern became less apparent, indicating an improvement in consolidation. The start-burst

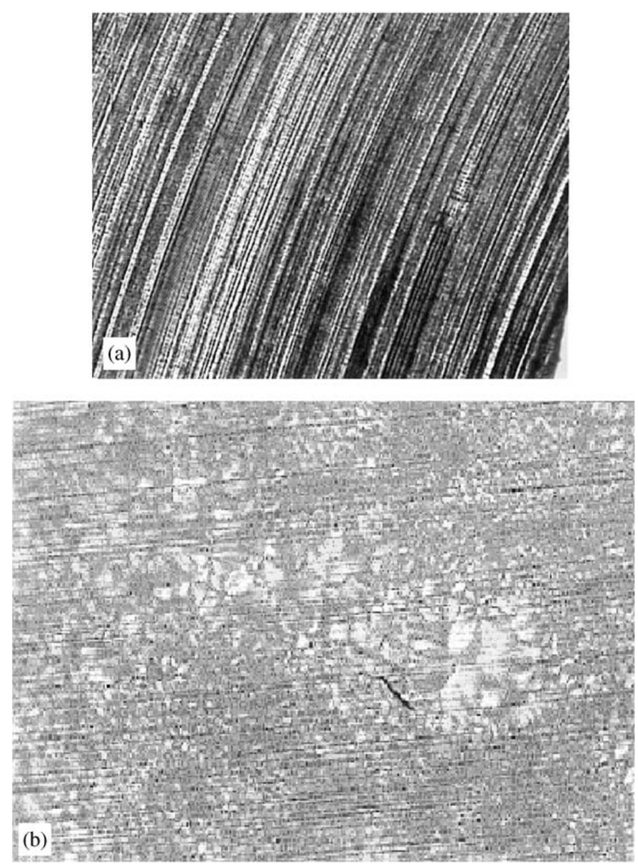

Fig. 1. Polarized light micrographs of the (a) Himont 1900 resin (b) GUR 405 resin hot isostatically pressed at 300°C and 138 MPa for 2 h, then cooled at a rate of 3°C/min. Clusters of spherulites can be observed in Himont 1900 sample (a).

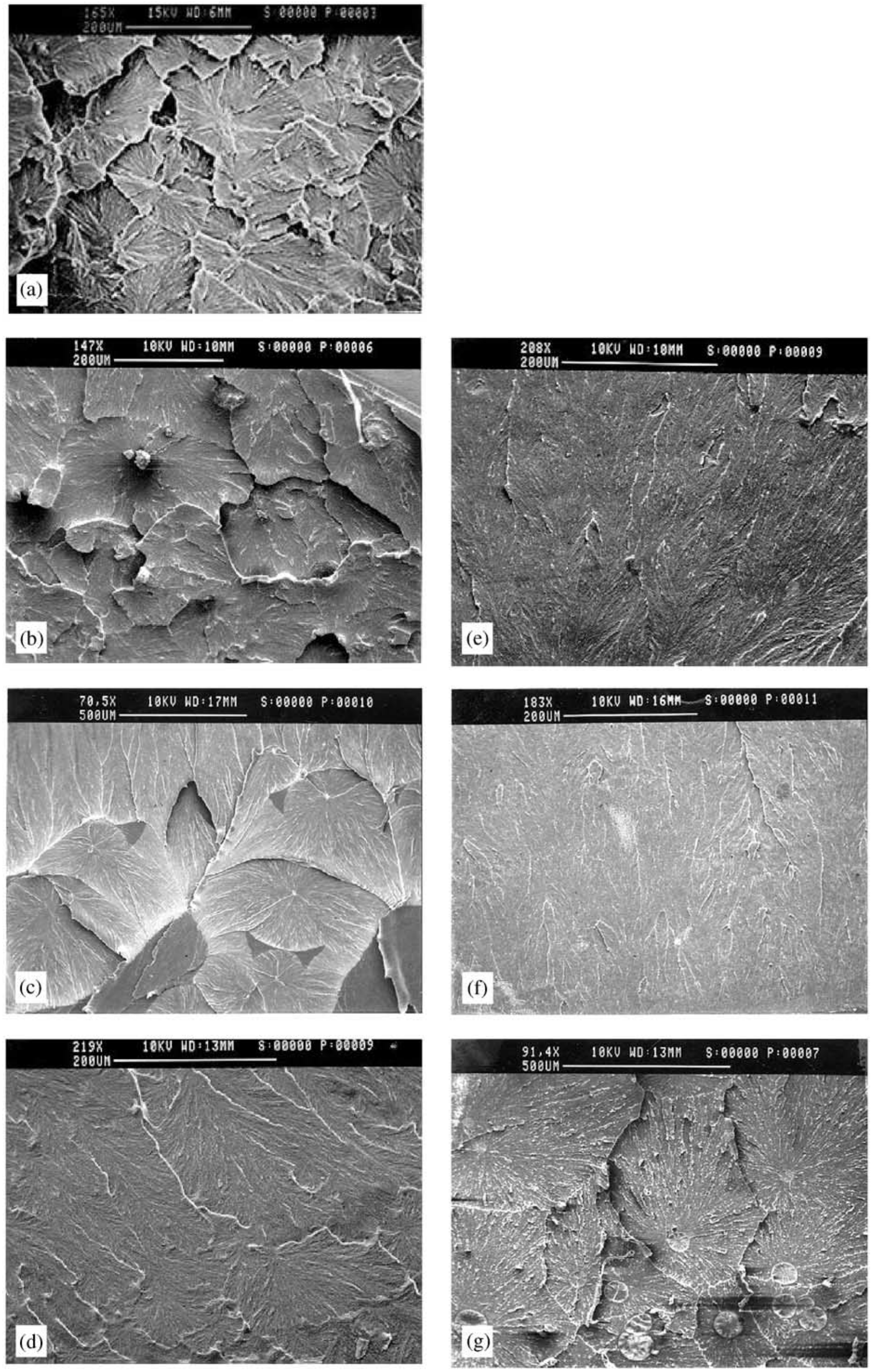

Fig. 2. Typical SEM micrographs of cryofractured surfaces of: **(a)** Ram extruded material (GUR 415 resin), GUR 405 resin that was hot isostatically pressed at **(b)** 210°C, **(c)** 250°C, **(d)** 300°C, and Himont 1900 resin that was hot isostatically pressed at **(e)** 210°C, **(f)** 250°C, **(g)** 300°C. The GUR 405 and Himont 1900 specimens were hot isostatically pressed at 138 MPa for 2 h, then cooled at a rate of 3°C/min.

morphology was not observed in the Himont 1900 resin processed at 210°C and 250°C, indicating better consolidation. The Himont 1900 resin consolidated at 300°C showed a spherulitic morphology (about 50 μm in diameter) on the cryofractured surface.

Fig. 3 shows representative micrographs of the solvent etched surfaces of the materials studied. The SEM analysis indicated extraction of material near the virgin resin powder boundaries. The particle structure was evident in both the ram extruded material and the GUR 405 sample processed a 210°C (Fig. 3a and b). At the processing temperature of 250°C, GUR 405 resin showed a more diffuse particle structure, indicating improvement in consolidation (Fig. 3c). At 300°C, there

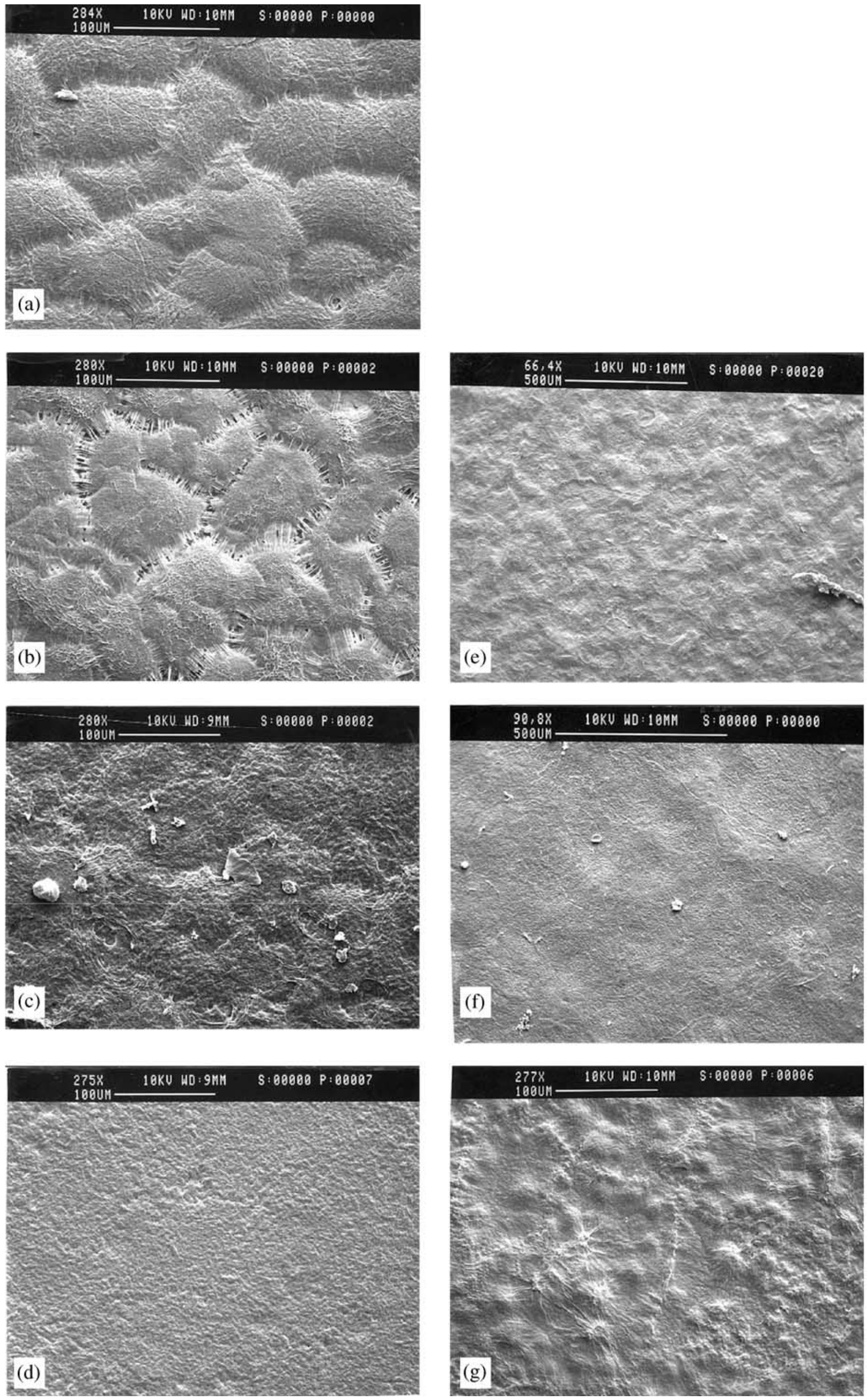

Fig. 3. Typical SEM micrographs of the solvent etched surfaces of all: (a) Ram extruded material (GUR 415 resin), GUR 405 resin that was hot isostatically pressed at (b) 210°C, (c) 250°C, (d) 300°C, and Himont 1900 resin that was hot isostatically pressed at (e) 210°C, (f) 250°C, and (g) 300°C. Etching was by immersion of a polished surface Decalin at 150°C for 45 s. The GUR 405 and Himont 1900 specimens were hot isostatically pressed at 138 MPa for 2 h, then cooled at a rate of 3°C/min.

was no evidence of particle structure, confirming significant improvement in consolidation. The solvent etched surface of the Himont 1900 resin processed at 210°C showed thinner particle boundaries as compared to the GUR 405 resin consolidated at the same temperature. At 250°C, the particle boundaries were no longer visible, indicating a well consolidated material. The solvent etched surface of Himont 1900 resin processed at 300°C showed a bumpy surface attributed to the presence of spherulites.

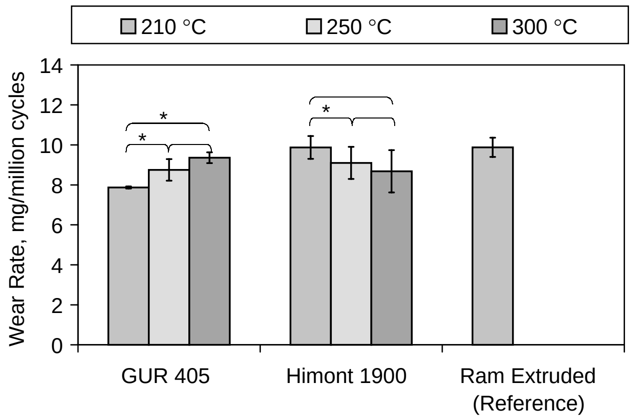

Fig. 4. Effect of processing temperature on the bi-directional pin on disc wear rate (mg/million cycles) of the GUR 405 and Himont 1900 resin. The ram extruded material is also shown for comparison.

Fig. 4 shows the effect of processing temperature on the wear rate of the various preparations of the GUR 405 and Himont 1900 resin. Ram extruded GUR 415 material is also shown for comparison. The ANOVA analysis showed that wear rate did not differ by resin type ($p = 0.19$). Similarly, the effect of consolidation temperature on wear rate was not significant ($p = 0.35$). The wear rate of GUR 405 resin increased with the processing temperature while the wear rate of Himont 1900 resin decreased with processing temperature. This interaction between the two factors was not significant ($p = 0.05$). The wear rate of the ram extruded material with its fusion defects and visible flake boundaries was comparable to those of the hot isostatically pressed GUR 405 and Himont 1900 resins even with varying degrees of consolidation.

4. Discussion

The degree of consolidation of both hot isostatically pressed type of specimens appeared to increase with increasing processing temperature. This improvement in increasing degree of consolidation is attributed to the increased chain mobility at higher processing temperatures. The Himont 1900 resin showed better consolidation than the GUR 405 resin at all consolidation temperatures studied. The number of fusion defects present in samples processed at 210°C was reduced by increasing the pressing temperature. Similarly, the extent of hot Decalin etching of the interparticle boundaries was reduced with increasing pressing temperature. The particle boundaries reflecting the powder flakes of the virgin resin were completely eliminated in the Himont 1900 resin at a consolidation temperature of 250°C. With GUR 405, the same level of consolidation was only achieved at the highest consolidation temperature, namely 300°C. The improved consolidation of the Himont 1900 resin over the GUR 405 may have been the result of lower average molecular weight and wider molecular weight distribution with the former. In addition, no spherulites were seen in the GUR 405 resin, while in the Himont 1900 resin spherulites were present at 250°C and 300°C. The formation of spherulites is an indication of increased chain mobility with the Himont 1900 resin when compared to GUR 405. The formation of spherulites might also be attributed to degradation in the Himont 1900 resin at higher processing temperatures, but, a preliminary infrared analysis of the consolidated resins showed no detectable carbonyl formation and hence no detectable degradation.

There were no significant changes with resin type and consolidation temperature on the adhesive/abrasive wear rate of UHMWPE. Overall the adhesive/abrasive wear resistance of all of the specimens of UHMWPE appeared to be independent of the processing temperature and was not a function of the degree of consolidation. This observation suggests that the adhesive/abrasive wear is a local surface process and is not affected by the bulk inhomogeneities in the material. It has been postulated that adhesive and abrasive wear takes place by the formation of a surface layer that is highly oriented in the direction of sliding induced by the uncoiling of the polymer molecules [16,17]. This oriented surface layer easily breaks up when the direction of sliding changes.

The present study showed that increasing the processing temperature of UHMWPE is accompanied by a marked improvement in its consolidation which was manifested by reduction in the number of fusion defects and visibility of flake boundaries upon extraction with hot Decalin. The adhesive/abrasive wear rate was independent of this improvement in the consolidation. Therefore, improving consolidation by increasing the processing temperature with hot isostatic pressing does not improve the wear behavior in total hip replacements.

Acknowledgements

The financial support for this project is provided by William H. Harris Foundation, Boston, MA.

References

[1] Wright TM, Bartel DL. The problem of surface damage in polyethylene total knee components. Clin Orthop Relat Res 1986;205:67–74.
[2] Kurth M, Eyerer P, Ascherl R, Dittel K, Holz U. An evaluation of retrieved UHMWPE hip joint cups. J Biomater Appl 1988;3:33–51.
[3] McKellop HA, Campbell P, Park SH, Schmalzried TP, Grigoris P, Amstutz HC, Sarmiento A. The origin of submicron

polyethylene wear debris in total hip arthroplasty. Clin Orthop Relat Res 1995;311:3–20.
[4] Wang A, Stark C, Dumbleton JH. Mechanistic and morphological origins of ultra-high molecular weight polyethylene wear debris in total joint replacement prostheses. Proc Inst Mech Eng Part H, J Eng Med 1996;210(3):141–55 [see comments].
[5] Muratoglu OK, Kurtz S. Alternate bearing surfaces in hip replacement. In: Sinha R, editor. Hip replacement. Current trends and controversies. New York, NY, 2002. p. 1–46.
[6] Kurtz SM, Muratoglu OK, Evans M, Edidin AA. Advances in the processing, sterilization, and crosslinking of ultra-high molecular weight polyethylene for total joint arthroplasty. Biomaterials 1999;20(18):1659–88.
[7] Rose R, Nusbaum H, Schneider H, Ries M, Paul I, Crugnola A, Simon S, Radin E. On the true wear rate of ultra high-molecular-weight polyethylene in the total hip prosthesis. J Bone Joint Surg 1980;62-A:537–49.
[8] Rose R, Radin E. A prognosis for ultra high molecular weight polyethylene. Biomaterials 1990;11(64–67.).
[9] Li S, Burstein AH. Ultra-high molecular weight polyethylene The material and its use in total joint implants. J Bone Joint Surg, Am 1994;76(7):1080–90.
[10] Olley RH, Hosier IL, Bassett DC, Smith NG. On morphology of consolidated UHMWPE resion in hip cups. Biomaterials 1999;20:2037–46.
[11] Mayor MB, Wrona M, Collier J, Jensen JW. The role of polyethylene quality in the failure of tibial knee components. In: Proceedings of the 39th Orthopaedic Research Society, San Francisco, CA, 1993.
[12] Landy MM, Walker PS. Wear of ultra-high-molecular-weight polyethylene components of 90 retrieved knee prostheses. J Arthroplasty 1988;3(Suppl.):S73–85.
[13] Walker P, Blunn G, Joshi A, Sathasivam S. Modulation of delamination by surface wear in total knees. In: Proceedings of the 39th Annual Orthopaedic Research Society. San Francisco, CA, 1993.
[14] Blunn G, Joshi A, Walker P. Performance of ultra-high molecular weight polyethylene in knee replacement. In: Proceedings of the 39th Annual Orthopaedic Research Society. San Francisco, CA, 1993.
[15] Bragdon CR, O'Connor DO, Lowenstein JD, Jasty M, Biggs SA, Harris WH. A new pin-on-disk wear testing method for simulating wear of polyethylene on cobalt-chrome alloy in total hip arthroplasty. J Arthroplasty 2001;16(5):658–65.
[16] Edidin AA, Pruitt L, Jewett CW, Crane DJ, Roberts D, Kurtz SM. Plasticity-induced damage layer is a precursor to wear in radiation-cross-linked UHMWPE acetabular components for total hip replacement. Ultra-high-molecular-weight polyethylene. J Arthroplasty 1999;14(5):616–27.
[17] Jasty MJ, Goetz DD, Lee KR, Hanson AE, Elder JR, Harris WH. Wear of polyethylene acetabular components in total hip arthroplasty An analysis of 128 components retrieved at autopsy or revision operation. J Bone Joint Surg 1997;79(A): 349–58.