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Static fracture resistance of ultra high molecular weight polyethylene using the single specimen normalization method

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Abstract

Fracture of Ultra High Molecular Weight Polyethylene (UHMWPE) components used in total joint replacements is a clinical concern. UHMWPE materials exhibits stable crack growth under static loading, therefore, their fracture resistance is generally characterized using the J-R curve. The multiple specimen method recommended by ASTM for evaluation of the J-R curve for polymers is time and material intensive. In this study, the applicability of a single specimen method based on load normalization to predict J-R curves of UHMWPE materials is evaluated. The normalization method involves determination of a deformation function. In this study, the J-R curves obtained using a power law based deformation function and the LMN curve based deformation function were compared. The results support the use of the power law based deformation function when using the single specimen approach to predict J-R curves for UHMWPE materials.

1. Introduction

Ultra high molecular weight polyethylene (UHMWPE) components frequently compose one-half of the articulating bearing couple in total joint replacements. As such, the articulating surface is subject to damage and wear and, under certain conditions, the components may also be at risk of fracture [1]. Therefore, there has been much interest in the evaluation of fracture resistance of different UHMWPE formulations under static and cyclic loading conditions [2–6].

The fracture toughness of ductile materials is often characterized by the J-integral approach developed by Rice [7]. Materials that exhibit stable crack growth under static loading are generally characterized by the crack growth resistance curve (J-R curve) where J integral value is plotted as the function of crack extension, Δa . J-R curves have been used successfully to characterize the fracture toughness of many ductile polymers [8–10]. ASTM recommends both multiple specimen and single specimen methods for metals (ASTM E 1820 [11]) but only the multiple specimen method is recommended for polymers (ASTM D6068 [12]). The multiple specimen method, though straightforward and effective, is time and material intensive. For example, ASTM D6068 [12] recommends a minimum of 7 specimens to generate the J-R curve of a polymer.

The single specimen method allows for the generation of the J-R curve through a single fracture test. Chung and Williams [8] conducted single specimen tests for ductile polymers using the elastic-compliance method recommended by ASTM E1820 [11] for metals. The reliability of the elastic compliance method is questionable for ductile polymers due to the

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presence of hysteresis in the load displacement curve, which makes accurate prediction of crack extension from compliance difficult. However, the single specimen method based on (load) normalization offers an easy and effective alternate approach to obtain J-R curves. Many ductile polymers has been tested successfully using the load normalization method [9, 13, 14].

Recently, a single specimen method for J-R curve determination based on load normalization was successfully applied to UHMWPE [15]. That study used a deformation relationship based on the LMN function (see below). However, studies conducted in other semicrystalline polymers recommend a power law based deformation relationship [13, 14]. The objective of this study was to use the single specimen normalization method to compare the LMN and power law deformation functions for determination of the J-R curve for several conventional and crosslinked UHMWPE formulations.

2.0 Theoretical background

2.1 Single specimen normalization method

The objective of any single specimen method including the normalization method is to obtain accurate crack length predictions using the load vs. displacement data alone. The normalization method involves separation of the load, P , into a geometry function, $G(a/W)$, and a deformation function, $H(v_{pl}/W)$ [16].

$$P = G(a/W) \cdot H(v_{pl}/W) \quad (1)$$

where a is the crack length, W is the specimen width, and v_{pl} is the plastic displacement,

2.1.1 Geometry and deformation functions—The general form of the geometry function [17] is given by

$$G(a/W) = BW \left(\frac{W-a}{W} \right)^{\eta_{pl}} \quad (2)$$

where B is the specimen thickness and η_{pl} is a specimen geometry dependent exponent. For single edge notched bend (SENB) specimens, $\eta_{pl} = 2.0$ [17].

Using equation 1 and 2, the normalized load, P_n is defined as

$$P_n = \frac{P}{G(a/W)} = \frac{P}{BW \left(\frac{W-a}{W} \right)^{\eta_{pl}}} = H(v_{pl}/W) \quad (3)$$

The functional forms of the deformation function, $H(v_{pl}/W)$ that are commonly used are the power law [18] and the LMN function [19].

$$P_n = \beta (v_{pl}/W)^n \quad (4)$$

$$P_n = \frac{[L + M(v_{pl}/W)]}{[N + (v_{pl}/W)]} (v_{pl}/W) \quad (5)$$

where β and n are the coefficient and exponent in the power law function and where L , M , and N are three constants in the LMN function.

2.1.2 Power law based deformation function—To determine the unknown constants (β , n) for the power law (Equation 4), at least two calibration points are required. The calibration points are points at which load, displacement and crack length are known. Thus, the final crack length point and an initial crack length point can be used as calibration points. The final crack length point is defined by the final load, final displacement and final crack length (Figure 1a). However, the initial crack length point is not so clear, because a point has to be chosen at which there has been substantial plastic displacement but no stable crack growth. Such a point is typically difficult to determine. Therefore, instead of an initial crack length point, a set of calibration points are taken within a displacement range, hereafter referred to as separable blunting zone (SBZ) [19]. In the SBZ, crack extension is assumed to be only due to blunting.

The calibration points in the SBZ are obtained using a forced blunting assumption [19]. Several points are chosen in the SBZ (Figure 1a). J is computed at these points using the load and displacement at these points and the initial crack length, a_0 (Equation 6)

$$J = \frac{\eta_{pl} U}{B(W - a_0)} \quad (6)$$

where, U is the area under load vs. displacement curve. The crack is then given forced blunting extension as described by

$$a_b = a_0 + \frac{J}{2m\sigma_y} \quad (7)$$

where a_b is the crack length at the forced blunting calibration points, m is the crack tip constraint factor, and σ_y is the flow stress of the material.

The fitting constants (β , n) of the power law based deformation function are obtained using equations 3 and 4.

2.1.3 LMN function based deformation function—To obtain the constants (L , M , N) of the LMN function (Equation 5), three calibration points are required. The final crack length point can be considered as one calibration point (point A). A set of forced blunting calibration points as described in section 2.1.2 can be taken as a second calibration point (points B_j). The third intermediate calibration point is not based on crack length but rather on the reproducibility of load versus displacement [19]. A set of points (points C_j) are chosen at half the v_{plf} . The ordinate of the first point, C_1 , is equal to the ordinate of the maximum forced blunting calibration point (Figure 1b). Using the calibration points A , B_j , and C_j , the constants, L , M , and N are computed by an iterative routine [19]. For every calibration point, C_j a set of L , M , and N constants are determined and their average yields the best fit LMN function.

Having determined the fitting constants: (β , n) for the power law based deformation function and (L , M and N) for the LMN function based deformation function, the crack length can be calculated using equations 8 or 9 through a numerical routine.

$$\frac{P}{BW\left(\frac{W-a}{W}\right)^{\eta_{pl}}} = \beta(v_{pl}/W)^n \quad (8)$$

$$\frac{P}{BW\left(\frac{W-a}{W}\right)^{\eta_{pl}}} = \frac{[L+M(v_{pl}/W)]}{[N+(v_{pl}/W)]} (v_{pl}/W) \quad (9)$$

Once the instantaneous crack length values are determined, instantaneous values of J can be evaluated using equation 6. From the instantaneous values of J and a , the J-R curve can be obtained. For a detailed description of normalization procedure the reader is referred to Varadarajan [20].

Both the power law and the LMN function based deformation functions have been used by authors to obtain J-R curves for a variety of polymers [9, 13, 14, 21–23]. As noted above, Landes et al [15] used the LMN function to obtain J-R curves for UHMWPE. However, studies conducted on other semi-crystalline polymers (MDPE and polypropylene) indicate that a power law based deformation function resulted in more accurate J-R curves than an LMN function based deformation function [13, 14]. Therefore, it is of importance to determine the influence of the chosen deformation function on the predicted J-R curves.

The determination of an SBZ in which the forced blunting calibration points are obtained involves testing of a series of blunted crack tip specimens [14]. To minimize required testing, the influence of SBZ on the predicted J-R curves for UHMWPE also needs to be determined. Finally, it is of importance to determine the crack tip constraint factor, m , which is appropriate for UHMWPE. The crack tip constraint factor (equation 8), used to determine forced blunting calibration points, is dependent on material, specimen geometry and loading conditions. For many ductile polymers, m values ranging from 0.5 to 2 have been used [8, 13, 14].

3. Materials and Methods

Five UHMWPE materials were examined in this study:

1. A sequentially crosslinked and annealed UHMWPE (“M1”). Compression molded GUR 1020 bar stock (Stryker Orthopaedics, Mahwah, NJ) subjected to 30kGy gamma radiation followed by annealing at 130°C. This process cycle was sequentially repeated twice more to accumulate a total dose of 90 kGy.
2. Ram extruded GUR 1050 (Stryker Orthopaedics, Mahwah, NJ) subjected to 30kGy gamma sterilization in Nitrogen (“M2”).
3. Compression molded GUR 1020 (Stryker Orthopaedics, Mahwah, NJ) subjected to 30kGy gamma sterilization in Nitrogen (“M3”).
4. As-received GUR 4150 (MediTech Medical Polymers, Fort Wayne, IN, “M4”).
5. Ram extruded GUR 1050 (Stryker Orthopaedics, Mahwah, NJ) subjected to 100kGy electron beam crosslinking followed by remelting at 150°C (“M5”).

Experimental data used to generate J-R curves using a multiple specimen approach were obtained from earlier studies [24]. The experimental setup and the procedure to obtain the J-R curves using a multiple specimen method are briefly described. For a detailed description, the reader is referred to Dapp [25]. Single edge notch three point bend (SENB) specimens were machined. Thickness (B), width (W) and length (L) of the specimen were 20mm, 40mm, and 180 mm, respectively. The specimens were polished and precracked.

Precracking was accomplished by pressing a razor blade into the notch at a controlled displacement rate (0.06 mm/min) to introduce a 3.5 mm long precrack. After razor sharpening, all the specimens fell in the ASTM D6068 [12] prescribed range of $0.5 < a/W < 0.65$. Specimens were stored at -20°C until testing to minimize potential oxidation of the material [26].

Three point bending tests ($n = 7$ to $9/\text{material group}$) were performed in ambient air at a crosshead speed of 0.85 mm/s using a servo hydraulic materials testing machine (Instron corporation, Canton, MA). The multiple specimen method [12] was used to obtain the J-R curves. The J integral was calculated using equation 8. For the SENB specimen, $\eta_{pl} = 2$ [12]. To measure crack extension, Δa , the tested specimens were fractured following soaking in liquid nitrogen immediately following testing. Final crack length was calculated by measuring the crack length at five equally spaced points along the crack front [12]. J- Δa data points were fitted to a power law to determine the J-R curve for each material.

J-R curves were also generated using the single specimen normalization method with both the power law and the LMN function based deformation functions. Six forced calibration points were determined in the SBZ using equation 7 with a nominal flow stress, $\sigma_y = 24.5\text{MPa}$ (yield stress) for all the UHMWPE materials [25]. The influence of crack tip constraint factor on the predicted J-R curves was examined by setting m to 1.5, 2 or 4. The influence of SBZ range on the predicted J-R curves was evaluated using three displacement (v) ranges (denoted as A, B and C) as follows: A = $3 < v < 5\text{mm}$; B = $3 < v < 7\text{mm}$; and, C = $3 < v < 10\text{mm}$. The influence of crack tip constraint factor and SBZ range was studied for M1 and M4. At 10 mm displacement, considerable crack extension (about 1.5 mm) was observed for material M1, therefore the influence of the SBZ range C was not considered for M1.

J vs. Δa data sets were fitted to the power law

$$J = C_1 \Delta a^{C_2} \quad (10)$$

where, C_1 is the coefficient and C_2 is the exponent

The fitted data sets were examined in the log-log form,

$$\log J = C_2 \log \Delta a + \log C_1 \quad (11)$$

Statistical comparisons of slope, C_2 , and intercept, $\log(C_1)$ were performed using the linear test method ($p < 0.05$ taken as significant) to study the influence of SBZ range and m on the predicted J-R curves [27].

4. Results

The multi specimen J-R behavior for the five UHMWPE materials demonstrate that the as-received material (M4) had the highest J-R curve while the 100 kGy electron beam crosslinked material (M5) had the lowest J-R curve (Figure 2). The load vs. displacement behavior of all the specimens within a material group was very consistent. Therefore, for each material group, the load vs. displacement data for the specimen with the maximum crack extension (Δa) was used for the single specimen approach analyses.

4.1 Single specimen method

J-R curve predictions based on power law based deformation functions corresponded qualitatively well with the J-R curve obtained using the multi specimen method for each material (Figure 3). For materials M2, M3, and M4, the SBZ range A = $3 < v < 10$ mm was found to predict J-R curves that corresponded qualitatively well with the J-R curves obtained using the multi specimen method (Figure 3). For materials M1 and M5, the SBZ range A = $3 < v < 5$ mm was found to be more appropriate (Figure 3). For all materials, a constant value of $m = 2$ was satisfactory. For materials M2, M3 and M5, both the power law and the LMN function based deformation functions resulted in virtually identical J-R curves that corresponded qualitatively well with the multi specimen J-R curves. However, for materials M1 and M4, the J-R curves predicted by the power law based deformation function were conservative as compared to those predicted by the LMN function based deformation function (Figure 3).

4.2 Influence of separable blunting zone (SBZ) range on the J-R curves

For material M1, it was found that using SBZ range A or B did not have a significant effect ($p > 0.05$) on the J-R curves (Figure 4a). However, for the LMN function based J-R curves (Figure 4b), the larger SBZ range, B, resulted in J-R curves that were not accurate for smaller Δa ($\Delta a < 0.3$ mm). For material M4, it was found that using SBZ range A, B, or C did not have a significant effect ($p > 0.05$) on the J-R curves predicted using the power law based deformation function (Figure 5a). However, the SBZ range had a significant effect ($p < 0.05$) on the LMN function based J-R curve (Figure 5b).

4.3 Influence of crack tip constraint factor (m) on the J-R curves

For the M1 material, the crack tip constraint factor, m did not have a significant effect ($p > 0.05$) on the J-R curves obtained using either fitting method (Power law and LMN function) except at smaller crack extensions ($\Delta a < 0.4$ mm, Figure 6). For the highest toughness material, M4, m had a significant effect ($p < 0.05$) on the J-R curve with both fitting methods. Lower values of m resulted in conservative J-R curves compared with the multi-specimen curve. For both fitting methods, the J-R curves predicted with $m = 2$ corresponded qualitatively well to the J-R curves obtained by the multi specimen method (Figure 7).

5. Discussion

The applicability of a single specimen method based on normalization to predict J-R curves for different formulations (both conventional and crosslinked) of UHMWPE was demonstrated. The J-R curves predicted using the power law based deformation function were found to be less sensitive to separable blunting zone range and crack tip constraint factor as compared to the J-R curves generated using the LMN function based deformation function (Figures 4 – 7).

To determine the separable blunting zone range, where load is separable and where crack length is constant, a separation parameter, S_{pb} , as suggested by Cassanelli et al [28] is generally used. The separation parameter is defined as

$$S_{pb} = \frac{P(a_p; v_{pl})}{P(a_b; v_{pl})} \text{ at constant } v_{pl} \quad (12)$$

where, p and b refer to a precracked and blunt notched specimen, respectively. After the non-separable initial region, the separation parameter, S_{pb} , remains constant. The value of the plastic displacement, where, S_{pb} begins to be constant, defines the lower limit of the

separable blunting zone. The value of plastic displacement at which crack growth initiation takes place defines the upper limit of the separable blunting zone. Thus, to define the limits of the separable blunting zone, ideally, blunt notched specimens should be tested.

The present analysis was performed using the experimental data obtained in earlier studies [24]. Thus, it was not possible to make blunt notched specimens. Therefore, in this study, a sensitivity study on the effect of SBZ range on the predicted J-R curves was performed. Interestingly, the J-R curves predicted using the power law based deformation function was found to be unaffected by the SBZ range for the UHMWPE materials (M1 and M4). This finding suggests that it may not be necessary to test blunt notch specimens to determine the SBZ range for UHMWPE materials.

With regard to crack tip constraint factor, m , the J-R curves predicted using the power law based deformation function were less sensitive to m as compared to the J-R curves generated using the LMN function based deformation function. Therefore, accurate determination of m may not be necessary for UHMWPE materials and $m = 2$ can be generally used for UHMWPE materials.

Overall, the findings of this study suggest that the power law based deformation function is less sensitive to separable blunting zone range and crack tip constraint factor selection than is the LMN function based deformation function for the determination of J-R curves of UHMWPE materials. The LMN function involves determination of three coefficients (L, M, and N) as compared to the power law which involves evaluation of only two coefficients. Moreover, determination of L, M and N involves a tedious iterative computational routine. In addition, the values of L, M and N depend on the choice of the intermediate calibration point. Taken together, the use of the power law based deformation function is recommended to predict J-R curves for UHMWPE materials using a single specimen.

6. Conclusions

A single specimen technique based on normalization was demonstrated to predict J-R curves well for five UHMWPE materials that spanned a range of fracture toughness. The J-R curves predicted using the power law based deformation function were less sensitive to the normalization parameters (separable blunting zone range and crack tip constraint factor) as compared to the J-R curves predicted using the LMN function based deformation function. Therefore, this study supports the use of the power law based deformation function when using the single specimen approach to predict J-R curves for UHMWPE materials.

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(a)

(b)

Figure 1. Calibration points for the (a) Power law based deformation function and (b) LMN function based deformation function

Figure 2.

J-R curves for five UHMWPE formulations obtained through the multiple specimen method [24].

Figure 3.

J-R curves obtained by the single specimen normalization method for the five UHMWPE materials

Power law based deformation function: $m = 2$, $A = (3 < v < 5)$ for all materials

LMN function based deformation function: $m = 2$, $A = (3 < v < 5)$ for M1 and M5; $C = (3 < v < 10)$ for M2, M3 and M4

(a)

(b)

Figure 4. Effect of SBZ range on the J-R curve of UHMWPE material M1 ($m = 2$). a) Power law based deformation function; b) LMN function based deformation function

(a)

(b)

Figure 5. Effect of SBZ range on the J-R curve of UHMWPE material M4 ($m = 2$). a) Power law based deformation function; b). LMN function based deformation function

(a)

(b)

Figure 6. Effect of crack-tip constraint factor, m on the J-R curve of UHMWPE material M1 obtained using SBZ range A ($3 < \nu < 5$) for the power law and LMN function based deformation functions

(a)

(b)

Figure 7.
Effect of crack-tip constraint factor (m) on the J-R curve of UHMWPE material M4 obtained using the SBZ range A ($3 < \nu < 5$) for the power law and C ($3 < \nu < 10$) for the LMN function based deformation functions