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Evaluation of Fracture Toughness of UHMWPE Used in Orthopaedic Implants Through Essential Work of Fracture

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Summary: This study investigates the use of the essential work of fracture (EWF) test in UHMWPE for use in orthopedic implants. A simplest method to produce the notch and initial crack was used. The validity of the fracture toughness results obtained by this method was investigated to evaluate the possibility of using this technique in obtaining data for the design of orthopedic prostheses.

Introduction

Medical grade ultra-high molecular weight polyethylene (UHMWPE) remains the material of choice for the bearing surface in total joint replacement components. This polymer offers unique mechanical properties as well as biocompatibility. In its conventional form, UHMWPE has exceptional mechanical integrity owing to its chain entanglements, high tie molecule density, moderate crystallinity (40–60%) and very high molecular weight (3.5×10^6–6.0×10^6 g/mol).[1]

Nowadays, investigations involving UHMWPE for orthopedic applications, especially in arthroplasty (surgical repair of joint), have been seeking the balancing of the material properties. This balancing involves some competing properties such as the reduction of abrasive wear, avoiding or reducing particulate-induced osteolysis, ensuring oxidative stability, while minimizing the loss of mechanical properties, especially fatigue resistance and fracture toughness.[1,2]

Different methods have been used to determine the properties of fracture toughness of UHMWPE, such as measures of impact toughness, crack growth and J-integral.[3,4] In this study, the essential work of fracture (EWF) was used to determine the fracture resistance of ductile materials.[5,6] Apart from being a simple technique to be applied, the EWF technique allows obtaining toughness data of UHMWPE for use in orthopedic implants, independent of the test geometry, so that the data obtained can thus be applied in the development of new products.

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Essential Work of Fracture

The concept of essential work of fracture (EWF) was originally suggested by Broberg, and later developed by Cotterell and Mai.[7] This theory proposes that during the loading of a ductile solid with a pre-crack, the process of fracture and plastic deformation occur in different regions. The fracture process zone IFPZ and outer process dissipation zone OPDZ are shown in Figure 1 below.

During the crack growing process, a large part of the work of fracture that is dissipated in the plastic zone is not directly associated with the fracture process itself. Only the work used in the inner fracture process zone is dependent of the material tested.

Therefore, the total work of fracture (Wf) is result of a sum of two parts which

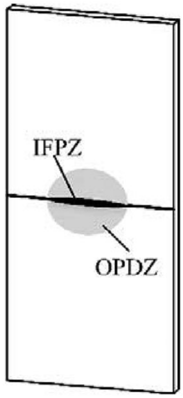

Figure 1.
Schematic diagram showing the fracture zones (a) (IFPZ: inner fracture process zone, OPDZ: outer process dissipation zone).[8]

consists of the essential work of fracture (W_e) and non-essential work of fracture (W_p) (Equation 1).

$$W_f = W_e + W_p \qquad (1)$$

Physically, W_e is the required work to create two new fracture surfaces and is consumed in the fracture process involved. In brittle fracture of glassy polymer, W_e is subsequently used to stretch and break the fibrils formed in the crazing zone at the crack tip (Figure 2 (a)). In the case of ductile polymers, W_e is consumed to create and subsequently break the necked zone ahead of the crack tip (Figure 2 (b)).[8]

The EWF method has been widely applied to various commodity plastics such as poly(ethylene terephthalate), polyethylene, polypropylene, and their blends. It has been proven theoretically and confirmed experimentally that the essential work of fracture corresponds to the critical J-integral value which is the reliable method for characterizing the fracture toughness of ductile polymeric materials.[9,10]

Experimental Part

The UHMWPE used was the GUR1050 produced by Ticona, specifically for the use in orthopedic implants. It was provided in the form of rods shaped by Orthoplastics. For the EWF test, we used DDEN-T (double edge-notched tensile) specimens (Figure 3). Usually the initial crack is produced using a razor blade. In the present work a constant profile knife with an alternating linear movement was used. The knife profile used has two sides, one to create a notch and the other to produce the initial crack required for the test. The device that was used to notch the specimens was also developed to guarantee the perfect symmetry of the notches and cracks produced. Five different nominal ligament lengths, ranging from 9 to 24mm, were used. However, for the calculations, the length of the ligament was determined using an image analyzer. A photography

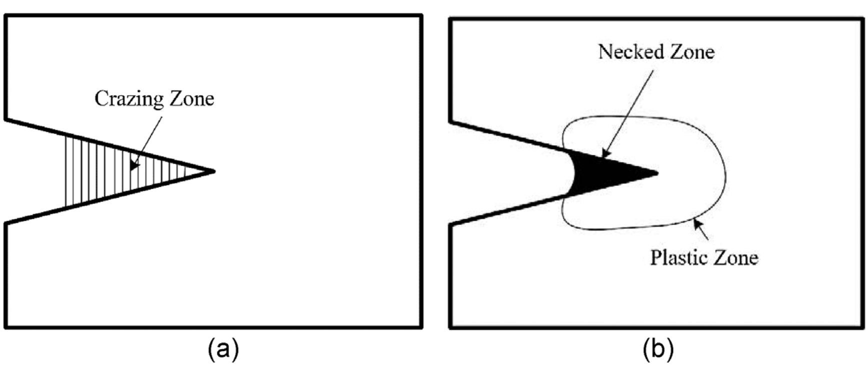

Figure 2.
Process zone in glassy polymers (a) and in ductile polymers (b).

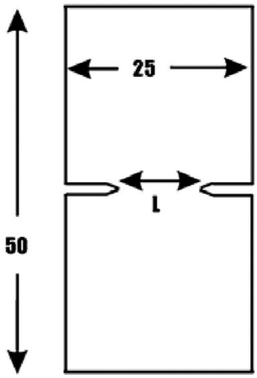

Figure 3.
DDEN-T specimen used for the EWF test. The letter L indicates the length of the ligament.

of the DDEN-T specimen and a reference scale was obtained from Figure 4 and analyzed in imageJ software to obtain the real ligament length. Previous works has showed that the small differences between the real size and the nominal size can lead to a poor curve fitting and therefore to a small reliability of the data.[11] For the production of the double notch in the specimens, we used a device built to assure the symmetry of the specimen and a constant profile of the notch. The test was performed on the machine INSTRON 5569 at a speed of 10 mm/min. The same equipment was also used for a uniaxial tensile testing carried out according to ISO 527-1 and ISO 5834-2. Type 1B at were used at a fixed displacement rate of 100 mm/min.

Results and Discussion

Figure 5a shows the force-displacement curves obtained for the EWF test resulting from the length of ligament used. Based on these figures, the energy under the curve was determined as the total work of fracture (W_f).

The energy required for fracture (We) can be considered to be a pure crack resistance parameter. As a result, the value of We is essentially a surface energy and is proportional to the ligament length l ($l = W - a$) for a given thickness, and W_p is an energy of volume proportional to l^2, therefore, W_f can be written as follows:

$$W_f = w_e tl + \beta w_p tl^2 \quad (2)$$

$$w_f = \left(\frac{w_f}{tl}\right) = w_e + \beta w_p t \quad (3)$$

where β is a shape factor associated with the volume of the plastic deformation zone an t the specimen thickness. In many studies, it is assumed that w_e is a material constant and W_p and β are independent of l.[9,10] When W_f is plotted against l, then there is a linear relationship between the two. Obtaining

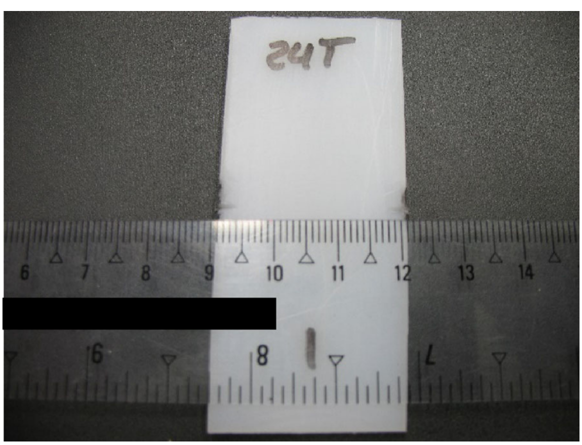

Figure 4.
View sample of specimen and scale used to measure the length of the ligament.

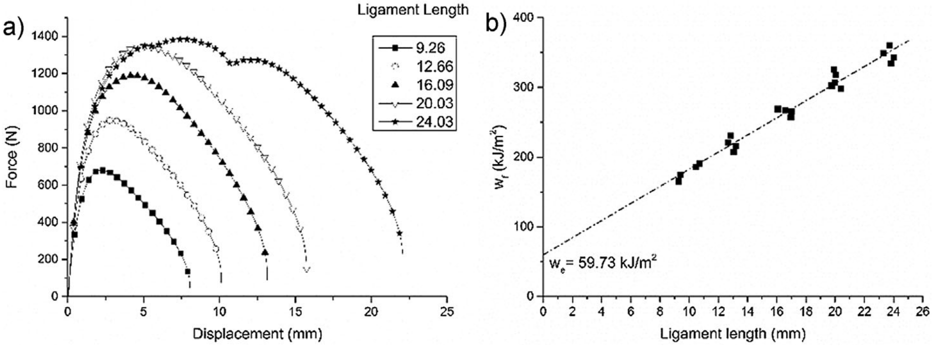

Figure 5.
Results of the EWF test. In (a) it is possible to observe the results of force versus displacement obtained for different bond lengths. In (b) the specific curve of the total work in function of the bond length is presented, where the essential work of fracture may be obtained from the linear adjustment of these points and extrapolating the curve to the length of ligament zero.

that linear relationship only occurs if the geometric similarity is maintained for all ligament lengths, since β changes with the geometry of the specimen and initial crack size. By extrapolating this data to $l = 0$, W_e can be determined from the intersection with the y-axis, and the slope coefficient at the beginning of the curve will provide the value of β. W_p, as can be seen in Figure 5b.

As it can be seen in Figure 5b, the behavior obtained for the sample was virtually linear, resulting in a correlation coefficient of 0.985. This is an indicator that the shape factor of the plastic zone (β) does not vary with the distance from the bond length for UHMWPE, and thus the EWF method can be used to measure the fracture toughness of UHMWPE. Another requirement for the values obtained by EWF to be valid is the finding that the UHMWPE is in a state of plane stress during the analysis. For the validation of the results for UHMWPE, we also performed the verification, based on the material flow stress and the ratio between the thickness and the bond length to ensure that it was in a state of plane stress during the EWF analysis.

If the ratio l/t is large enough to assure the condition of plane stress in the ligament area, it can be obtained from the W_f x l curve by extrapolating the straight line to the ligament length equal to zero, which is a material constant for a given thickness. With the reduction of the ratio l/t, the plastic repression increases and plane stress/plane strain transition can occur at a certain value of l/t, shifting the curve down.

Based on the study conducted by Hill,[12] the length of the ligament must be greater than the width of the specimen divided by 3. As the specimen width was 25 mm, the minimum acceptable length of ligament would be 8 mm. Another verification consisted in determining whether the maximum stress obtained in the test follows the relationship as a function of the yield stress, according to Equation (4).

$$\sigma_{Max} = 1,15\sigma_y. \tag{4}$$

For the yield stress of 22.46 MPa of UHMWPE, the maximum stress obtained in the EWF test should be approximately 25.94 MPa for the state of plane stress to be observed. Figure 6 shows the results of maximum stress obtained in the EWF test as a function of the bond length. As it can be seen, the values of maximum stress follow the Equation (6), indicates that the condition of state of plane stress has been observed.

Therefore, the value w_e (59.73 kJ/m2) was obtained in compliance with all the conditions for its validation, indicating that

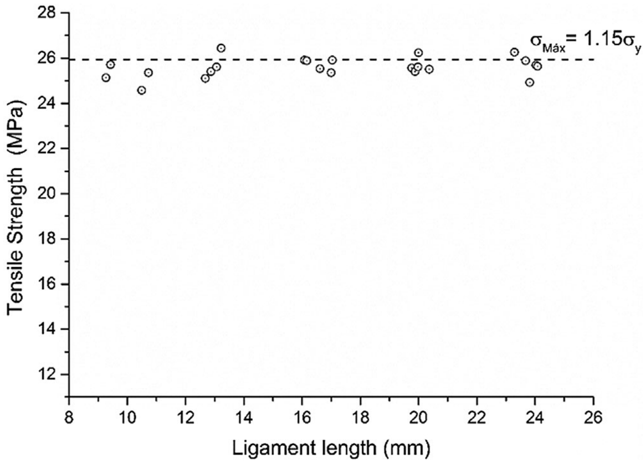

Figure 6.
Graph of the tensile strength in function of the length of ligament compared to 1.15 σ_y.

the EWF methodology can be applied for UHMWPE.

Conclusion

In search for a methodology to determine the value of fracture toughness of UHMWPE, regardless of the geometry of test employed, the essential work of fracture appeared to be a representative and easy performed method. Using a notching tool whose operation resembles the equipment used to notch Izod and Charpy test specimens, unlike the more common process with the use of razor blade, has proved effective. The results of essential work obtained by this method were similar to those obtained by other notching processes,[6] indicating that UHMWPE leads to a form shape of the plastic zone independent of the bond length, which is a necessary condition for the use of this methodology for the analysis of this material.

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