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# Impact fatigue response of ultra-high molecular weight linear polyethylene

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The impact fatigue response of ultra-high molecular weight linear polyethylene (UHMW LPE), in a special test, has been examined and the results are presented in this paper. In an attempt to understand the influence of high molecular weight on impact strength, identical measurements were made on a normal molecular weight linear polyethylene (NMW LPE). UHMW LPE is found to have a superior impact and impact fatigue behaviour to the NMW LPE. Almost all of the UHMW LPE materials perform equally well in the present impact fatigue test. However, one of the high bulk density UHMW LPE materials, resin G, performs quite poorly. Photomicrographs of the free surface of this material show that this may result from poor interparticle fusion during compression moulding.

## 1. Introduction

In this paper we examine the impact fatigue response of some ultra-high molecular weight (UHMW) linear polyethylene (LPE) materials. In an attempt to understand the influence of high molecular weight on impact behaviour, identical measurements were also made on a normal molecular weight linear polyethylene (NMW LPE).

The fact that makes the impact-fatigue test (to be discussed) attractive is that it is multifaceted. It evaluates a combination of impact and fatigue by measuring the cumulative damage in a specimen subjected to repeated impact blows. In addition, it also provides information about the notch sensitivity of UHMW LPE under a predetermined set of impact conditions similar to those which such a material might encounter in use. Thus, the present test comes very close to simulating the actual use condition for many conceivable applications, say for instance plastic gears, where impact fatigue testing in the presence of notches and flaws becomes very important.

It should be pointed out that some workers [1–4] have attempted to study the impact fatigue behaviour of materials. However, because of the many different variables involved, the results did not correlate well with those for the standard single blow impact tests. The rate of loading was found to have a significant effect on the repeated impact response [5]. Other external variables such as the energy level and frequency of the impact blow may also significantly affect the impact fatigue response of polymers. The effects of these variables, however, were not studied in the present work.

## 2. Materials

The UHMW LPE resins evaluated during the present study together with the designations employed to identify them in the rest of the paper are listed in Table I.

## 3. Apparatus

The Dynatup 8000 Drop Tower Impact machine was developed by Effects Technology Corporation and marketed by Tinius Olsen. The Machine consists of two essential parts: (a) the drop tower, and (b) the measuring circuit.

The drop tower and its components are shown

TABLE I List of UHMW LPE materials examined

| UHMW LPE resin | Reported intrinsic viscosity; $[\eta]$ $(\mathrm{d\,l\,g^{-1}})$ | Density of moulded sheets $(\mathrm{g\,cm^{-3}})$ | DSC melting peak temperature (° C) $(20^\circ\,\mathrm{C\,min^{-1}})$ |
|---|---|---|---|
| Resin A* | –§ | 0.936 | 143.6 |
| Resin B | 23 | 0.934 | – |
| Resin C | 23 | 0.934 | – |
| Resin D | 24–30 | 0.930 | 146.7 |
| Resin E | 13 | 0.935 | 143.9 |
| Resin F† | 19.8 | 0.929 | 143.9 |
| Resin G‡ | 13 | 0.935 | 143.3 |

*Sinterable grade.

†This material was selected as the candidate whenever it was decided to restrict parts of the study to only one material.

‡A high bulk density material with essentially spherical shaped particles.

§Reported molecular weight = $2.8 \times 10^6$.

in Fig. 1. It simply consists of a set of parallel rods over which a heavy weight slides uniformly and reproducibly; the weight is approximately 68 kg.

The measuring circuit consists of a gold foil 4-legged strain gauge bridge mounted on a reduced cross-section of a hardened rectangular bar which holds the striking head. A feature of the design is that a relatively high signal to noise ratio output is obtained. Under most conditions, vibration introduced into the measuring circuit during impact produces only small perturbations on the force–time trace generated during impact.

The output of the strain-gauge bridge is fed to a dual beam Tetronix oscilloscope (with appropriate amplifiers) and displayed as traces of force versus time, and energy versus time.

## 4. Experimental procedures

### 4.1. Sample preparation

All the 3.2 mm thick specimens employed in the present study were compression-moulded in a positive pressure vacuum press according to the following procedure: a weighed quantity of polyethylene powder was placed in the mould cavity. The heat was turned on and vacuum pulled on the mould cavity. A nominal pressure of approximately $70\,\mathrm{kg\,cm^{-2}}$ was then applied to the mould platens. After the temperature reached 204° C, conditions were maintained for ~20 min. The platen pressure was then raised to $134\,\mathrm{kg\,cm^{-2}}$ and maintained for one additional minute. The platens were cooled down to 25° C in ~20 min. while maintaining pressure at $134\,\mathrm{kg\,cm^{-2}}$. Finally, the moulding was recovered by gradually releasing the pressure.

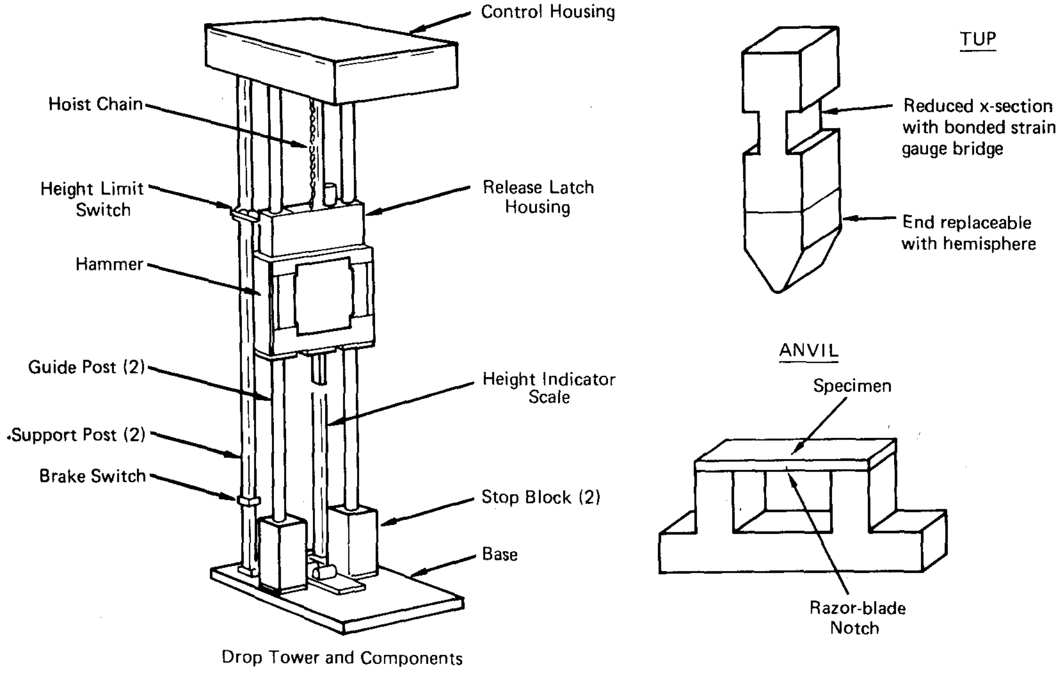

*Figure 1* Specimen and notch geometry relative to impact conditions.

All the 6.4 and 9.5 mm thick specimens were compression moulded in a Pasadena Hydraulics, Inc. press using the following schedule: The "window-mould" was placed between two lubricated aluminium foils backed up by steel plates, with the mould cavity containing a weighed quantity of polyethylene powder. The entire assembly was maintained at atmospheric pressure in contact with the preheated press-platens for ~ 5 min. The nominal pressure on the platens was raised to ~ 14 kg cm$^{-2}$ and the new conditions were maintained for ~ 9 min. The platens were then cooled down to 25° C in ~ 5 min. In order to avoid "sink marks" during cooling, the nominal pressure was gradually raised to approximately 70 kg cm$^{-2}$. Finally, the pressure was gradually released and the moulding recovered,

Constant cross-section bar specimens were milled and cut to length. A central transverse razor blade notch was induced in the specimens with a special jig designed for the purpose.

## 4.2. Testing procedure

The 76.2 mm long, 12.7 mm wide and 3.2 to 9.5 mm thick specimens were placed horizontally with the ends resting flat on supports, Fig. 1, and subjected to a central impact (a weight of ~ 68 kg dropped from a fixed height 30.5 cm) in the vertical (thickness) direction. The force–time and energy–time traces resulting from the impact can be and were sometimes recorded and photographed. The damage to the specimen caused by impact was estimated by monitoring the propagation of notch depth with a light microscope. The specimen was manually straightened and then subjected to another impact. The cycle was repeated until the specimen "failed". Failure was, rather arbitrarily, chosen as the point when the notch had propagated through at least $\frac{1}{3}$ of the thickness.

All tests were conducted in a controlled environment (22.7° C and 50% r.h.) and the specimens were preconditioned for at least 48 h prior to testing.

## 4.3. Developments of the present test

The present test evolved as a result of preliminary experimentation on the comparative impact response of UHMW LPE and NMW LPE in the Dynatup drop tower impact machine. Under the conditions of the present test, the *unnotched* specimens of NMW LPE and UHMW LPE did not fracture or even develop a visible crack after 10 repeated impact blows. In order to accelerate the fracture process and to get a semi-quantitative performance, a 0.254 mm radius notch was induced on the tensile side of the specimen[*]. Such specimens of NMW LPE fractured after 10 repeated impacts, while UHMW LPE specimens did not fracture at all. This then led us to the notch geometry of the present test – where we induce a sharp razor blade notch in the specimen.

# 5. Experimental results and discussion

## 5.1. General

The two sets of impact fatigue data for the different polyethylene samples tested are presented in Figs. 2 and 3 as plots of notch depth versus cumulative number of impacts. The only difference in the two sets of data is in variation of the initial notch depth.

In the NMW LPE samples, the notch propagates most of the way through the thickness at the very first impact. On the other hand, the UHMW LPE materials (except material G) sustain quite a few impacts before fracture and the notch

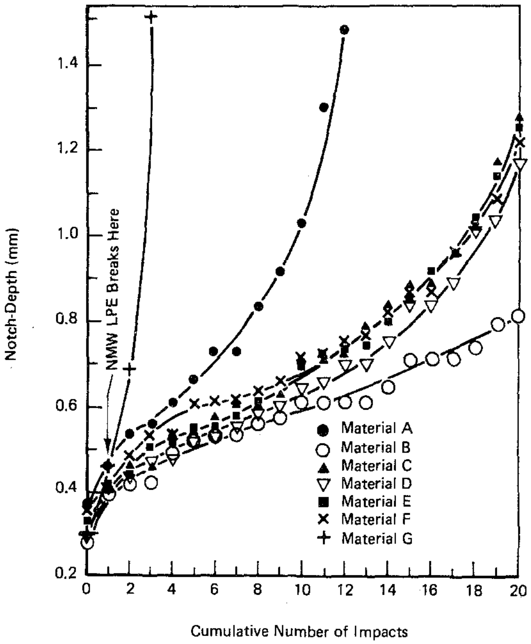

*Figure 2* Notch depth versus number of impacts for different UHMW LPE materials.

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[*] This also had the added advantage of generating useful information about the notch-sensitivity of UHMW LPE.

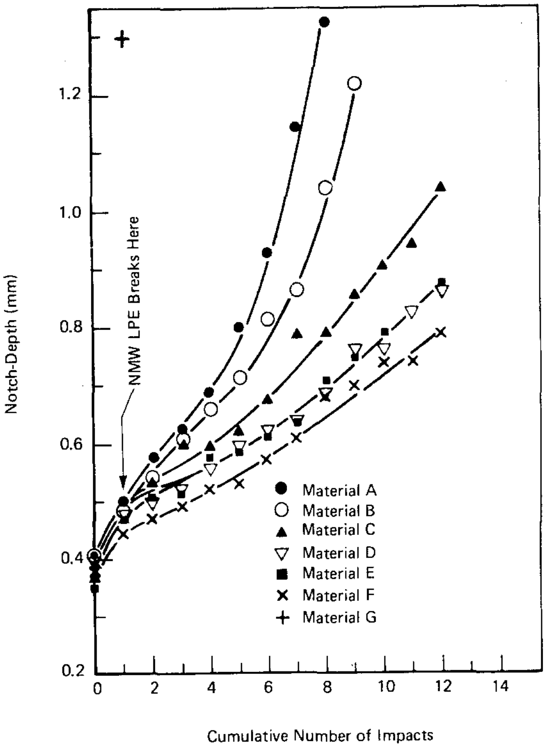

*Figure 3* Notch depth versus number of impacts for different UHMW LPE materials.

depth generally increases monotonically with the number of impacts. In some materials, after a few initial impacts, the rate of crack propagation decreases for a few impacts and then again increases subsequently becoming greater than the initial rate. This slowing down can be seen by the abrupt decrease in slope for some of the curves, and may be a result of notch tip blunting. Microscopic examination of specimens reveals that blunting of the notch tip does occur. Strain-hardening of the material in the vicinity of the notch tip could also lead to slower propagation of the notch, and UHMW LPE has been observed to strain-harden in the plastic region in independent uniaxial stress–strain measurements [6].

A first glance at the data in Figs. 2 and 3 indicates a rather wide spread between the response of different UHMW LPE materials. But before such a comparison can be made, one needs to consider the effect of the initial notch depth and of possible specimen-to-specimen variations on the data generated. These effects are considered in the next section.

## 5.2. Effect of initial notch depth and reproducibility

Fig. 4 shows the variation of notch depth with the cumulative number of impacts for all the different specimens of material F tested. The only variable from specimen to specimen, other than possible material inhomogeneity, is the initial notch depth. It should be pointed out that the unnotched samples of the same material when subjected to 100 repeated impact blows under identical conditions did not develop a crack. (The $x$-axis represents the impact fatigue response of an unnotched specimen.) The data in Fig. 4 show an increase in the rate of notch depth propagation with respect to the number of impact blows as the initial notch depth is increased. Possible reasons for a decrease in the slope after a few initial impact blows for some of the curves have been advanced earlier, namely blunting of the crack tip or strain-hardening of the material ahead of the crack tip.

Fig. 4 also appears to indicate that one could generate a master curve by translation of the

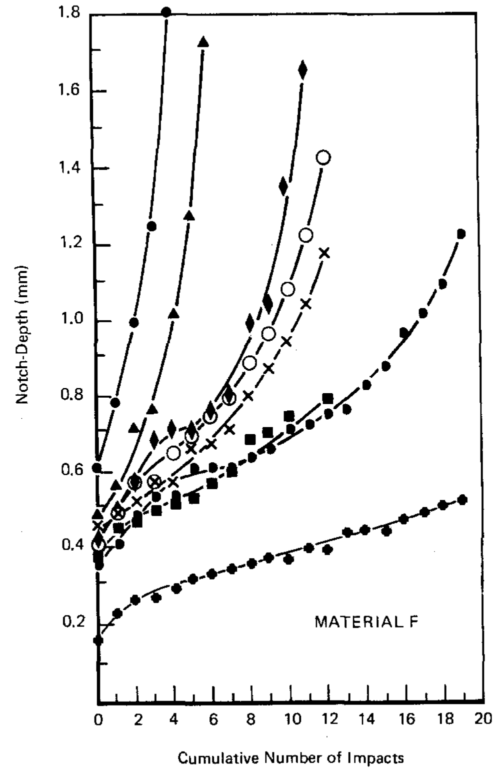

*Figure 4* Notch depth versus number of impacts for all different samples of material F; each symbol represents a different sample.

individual curves parallel to the $x$-axis. In fact, such an attempt was made, but was unsuccessful. Scatter in the data and more importantly the notch tip blunting with increasing cumulative number of drops and the resulting decrease in the rate of notch propagation are two complicating factors making it difficult to obtain a master curve from the data of Fig. 4.

In an effort to gain appreciation for the specimen-to-specimen variations in the impact fatigue response for a given UHMW LPE, 3 specimens of material F were moulded and tested under as identical conditions as possible and the results are shown in Fig. 5. As can be seen from Fig. 5, specimens numbered (2) and (3) have comparable initial notch depth, whereas specimen number (1) has a deeper initial notch. Comparing specimens (2) and (3) one does find some specimen-to-specimen variation which, however, is not large especially for a test of this kind. Specimen number (1), despite the deeper initial notch, shows slower crack propagation. This difference could be explained if this specimen had a more blunt initial notch. Thus, there is some specimen-to-specimen variation in the data which seems to become accentuated as the cumulative number of drops the sample is subjected to is increased. Any contribution to the observed variations due to possible material inhomogeneities has not been isolated.

Now we are in a position to compare the performance of different UHMW LPE materials and that is done in the following section.

### 5.3. Comparison of the impact fatigue response of different UHMW LPE materials

Figs. 2 and 3 illustrate the impact fatigue response of several different UHMW LPE materials. First inspection of Figs. 2 and 3 would indicate substantial difference in performance of the different UHMW LPE materials. However, in view of the inherent data scatter and the influence of the initial notch depth, these differences may not

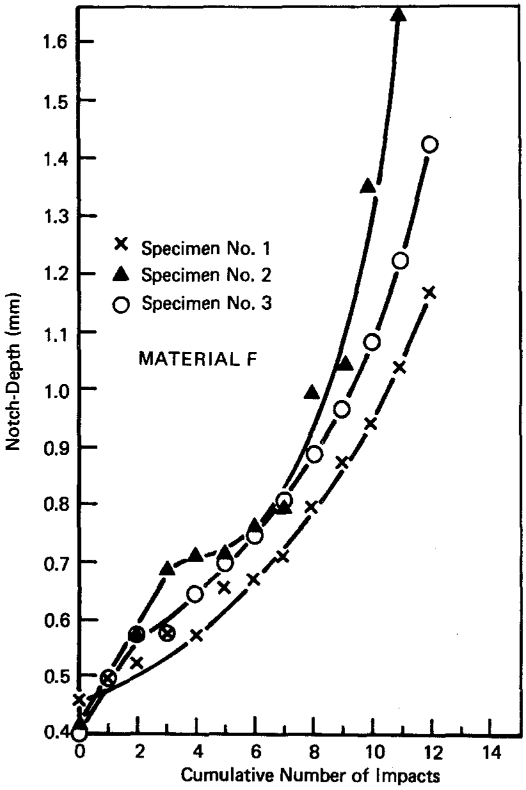

*Figure 5* Notch depth versus number of impacts for three different specimens of UHMW LPE, material F, showing reproducibility of data.

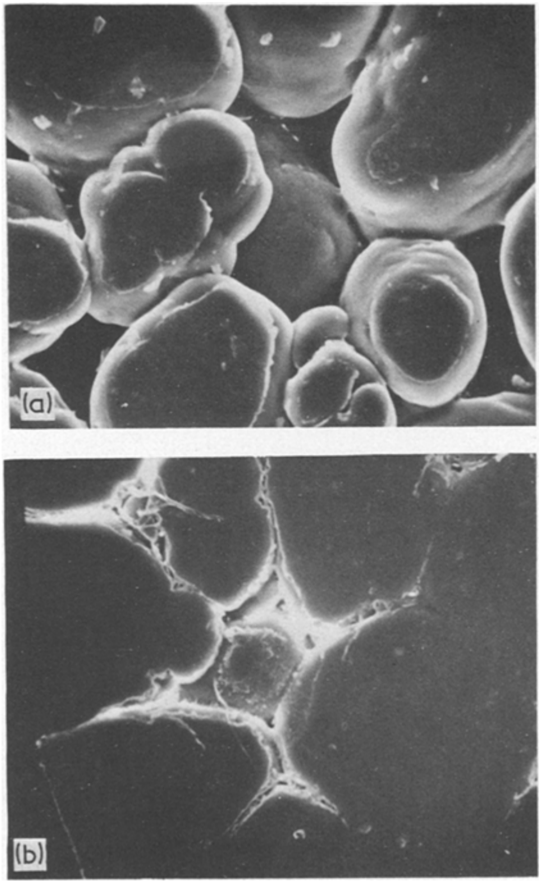

*Figure 6* Photograph (X 78) showing surface of material G, compression-moulded sample: (a) unfused zone, (b) partially fused zone.

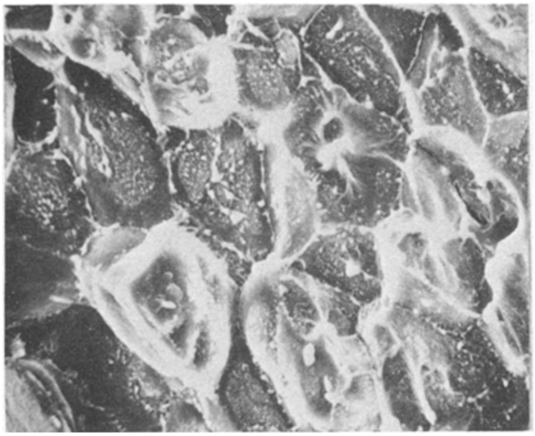

*Figure 7* Photograph (X 78) showing fracture surface of a tested sample of material G.

be as significant as the figures suggest. In fact, the only two UHMW materials that do not respond well in this test are material G and possibly material A – material G being the poorest, undergoing fracture under conditions of the present test in less than 3 impact drops.

All other UHMW LPE materials appear to be essentially comparable as far as their response to repeated impacts is concerned. The observation that UHMW LPE, G, performs poorly in this test may not be due to a poor intrinsic impact fatigue response, but rather it may be due to its poor compression moulding behaviour. For instance, even compression moulding this material at 215° C for 20 min does not yield a homogeneous and coherent moulding. The individual powder particles display a memory effect; the texture of the free surface of the moulding, Fig. 6, shows entities (with distinct boundaries) of the size of individual powder particles. The fracture surface of the tested sample also gives a similar appearance, Fig. 7. Thus, material G, upon compression moulding undergoes incomplete fusion and welding together of the individual powder particles. This may be the primary reason for the poor performance of material G in the present test.

## 5.4. Effect of specimen thickness

In the present test geometry, the ends of the specimen are not hinged or fixed; they are simply resting flat on the end supports. As a result, for a specimen of a given material with a fixed span, the amount of energy actually delivered to the specimen depends on the section modulus (= 2 x moment of inertia/thickness) of the beam specimen. If the section modulus of the specimen in the loading direction is too small, the specimen bends and travels away with the impacting tup. In this case, only a small amount of the impact energy goes into the specimen, which in turn results in a small increase in the notch depth. However, as the section modulus of the specimen is increased by increasing its thickness, it is more difficult to bend the specimen and the amount of energy delivered to the specimen increases. This results in faster notch propagation in thicker specimens. Another possible factor causing this effect could be the severity of stress distribution; thicker specimens are under a plane strain situation which leads to a triaxial stress state. Whatever the exact reason, this effect can be seen in Fig. 8 which shows the influence of varying specimen thickness from 3.2 to 9.5 mm, *maintaining the specimen span constant,* on the plot of notch depth versus number of impacts sustained. Part of this effect may be due to the

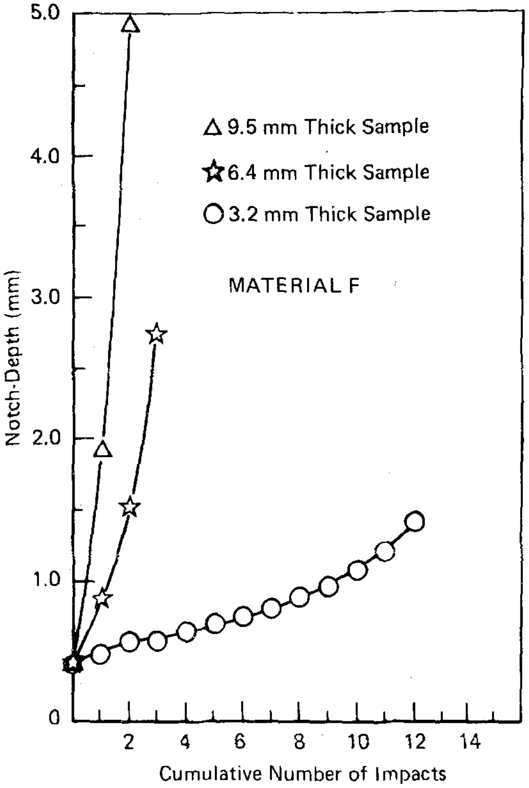

*Figure 8* Notch depth versus number of impacts as a function of specimen thickness for material F.

differences in the moulding procedures employed for the thick and the thin specimens. In any case, the rate of notch propagation in thicker specimens is much higher. For instance, the 9.5 mm thick specimen sustained only one or two impacts before failure, while the 3.2 mm thick specimen under identical conditions withstands more than 12 impacts before it "fails". Somewhat similar effects have been observed by others [7] who pointed out that while designing a beam for impact, just increasing the thickness of the beam does not improve its impact response.

It is extremely valuable to measure a material property which is independent of the test geometry. Apart from excluding the effects of test geometry, such a property may also be employed to characterize the material. The possibility of finding such a material property is being explored by the application of fracture mechanics for analysis of the impact fatigue data. This analysis shows promise of accounting for the effect of initial notch depth on the growth rate.

## 6. Conclusions

(1) UHMW LPE has superior impact and impact fatigue behaviour in comparision to NMW LPE.

(2) In the impact fatigue test examined in the present paper, almost all UHMW LPE materials perform comparably. Resin G performs poorly in comparison to other UHMW LPE materials.

(3) UHMW LPE, material G, performs very poorly in the impact fatigue test examined in this paper. This does not necessarily imply a poor intrinsic impact fatigue response of this material. Instead, it may just be a reflection on the poor interparticle fusion during compression moulding.

(4) For the given test geometry and constant specimen span, thin samples withstand more impact blows to failure than thick samples will withstand.

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