JOURNAL OF MATERIALS SCIENCE: MATERIALS IN MEDICINE **12** (2001) 621–628

The effect of molecular orientation and acetylene-enhanced crosslinking on the wear of UHMWPE in total artificial joints

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This paper investigates the benefits of combining roll-drawing and acetylene-enhanced crosslinking to alter the mechanical properties of the ultra high molecular weight polyethylene (UHMWPE) used in total hip and knee replacements, with the aim of improving its resistance to wear. UHMWPE was processed via crosslinking, roll-drawing and a combination of crosslinking and roll-drawing and subjected to gel content analysis, tensile tests, X-ray diffraction and wear tests using different types of motion and smooth and rough counterfaces.

Purely roll-drawn materials with length and width draw ratios of $\lambda_l \times \lambda_w = 1.3 \times 1.0$ and $\lambda_l \times \lambda_w = 1.6 \times 0.9$ respectively, were found to have lower wear factors in a unidirectional motion test with a rough counterface when compared to the virgin material.

The crosslinked roll-drawn material, with length and width draw ratios of $\lambda_l \times \lambda_w = 1.6 \times 0.9$, was seen to possess five crosslinks per initial number average molecule. This crosslinked and roll-drawn material showed 5.5 times less wear than the virgin material in a multidirectional motion test with a smooth counterface and 1.4 times more wear than the virgin material in a unidirectional motion test with a rough counterface.

Hence this study supports previous work by the authors that acetylene-enhanced crosslinked materials may show benefits for a total hip replacement, but only where the femoral head remains smooth. The improvements in wear with the roll-drawn material in unidirectional tests were smaller, but may prove to have some benefits in the knee.

Nomenclature

λ_l = length draw ratio
ε_n = engineering/nominal strain
σ_n = engineering/nominal stress
ε_t = true strain
σ_t = true stress
λ_w = width draw ratio
AEA = Atomic Energy Authority
A_o = original area
CoCr = cobalt chrome
Gel_{ir} = measured gel content of the irradiated and roll-drawn sample
Gel_r = measured gel content of the roll-drawn sample
$\mathrm{Gel}_{\mathrm{true}}$ = true gel content of the irradiated sample
IRC = interdisciplinary research center
K = wear factor
L = load
$M_{n,0}$ = initial average number molecular weight
NS = no significant difference with virgin material
p = probability determined from Students' t-test
para = parallel to draw direction
perp = perpendicular to draw direction
R_a = arithmetic mean of departure of the profile from the mean line
RD = roll-drawn
S = significant difference with virgin material
t_f = final thickness
t_i = initial thickness
UHMWPE = ultra high molecular weight polyethylene
UTS = ultimate tensile strength
V = volume loss
X = sliding distance
XLRD = crosslinked and roll-drawn
WAXD = wide-angle X-ray diffraction

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1. Introduction

It is widely recognized that the main cause of failure of metal-ultra high molecular weight polyethylene (metal-UHMWPE) total hip replacements is aseptic loosening of either the acetabular or femoral component. This has been attributed to the UHMWPE debris produced, which stimulates macrophage activity. Macrophages are cells that engulf wear particles and in so doing activate osteoclasts (bone removing cells) which result in bone resorption (osteolysis), leading to loosening and failure of the implant. It is of importance, therefore, to reduce the wear rate of UHMWPE and so minimize the number of wear particles [1].

Previous work carried out by the authors showed that acetylene-enhanced crosslinked UHMWPE produced 9.3 times less wear ($p < 0.001$) than virgin UHMWPE in a multidirectional smooth pin-on-plate test [2]. This is consistent with current work of other groups on crosslinked materials such as McKellop *et al.* [3]. However the acetylene-enhanced crosslinked material did not show beneficient wear properties in unidirectional tests or against rough counterfaces. Wang *et al.* [4] suggested that wear induced orientation produced as a result of unidirectional smooth tests might be responsible for the low wear factors produced when compared to a multidirectional smooth test. It was, therefore, hypothesized that UHMWPE processed using both roll-drawing (giving it uniaxial orientation) and acetylene-enhanced crosslinking might produce a material that exhibits lower wear in both multidirectional and unidirectional tests. This lower wear rate in turn would reduce the number of wear particles and decrease the likelihood of osteolysis.

The aim of this study was to ascertain whether crosslinking a uniaxially oriented polyethylene would produce a material with lower wear rates than its virgin material in both unidirectional and multidirectional wear tests.

2. Materials

Two different materials were produced as part of this study: (i) purely roll-drawn UHMWPE and (ii) acetylene-enhanced crosslinked roll-drawn UHMWPE for comparison with purely acetylene-enhanced crosslinked UHMWPE that was produced and tested in an earlier study [2]. Although UHMWPE of grade GUR 1120 was used in this study and UHMWPE of grade RCH 1000 was used in a previous study [2], they should have fairly similar properties. Basically RCH 1000 is an older title for GUR 1120. There may be differences between these two materials but this is only because they are different batches. The processing methods used to manufacture the virgin materials were the same.

2.1. Method of roll-drawing

The base polymeric material was heated up in an oven to 110 °C and then rolled through a rolling mill at the same time as a tensile force was applied by a caterpillar puller (see Fig. 1). The rolls and caterpillar puller were stopped with the product still being gripped at both ends under tension, enabling it to cool and retain its deformation. Once the material had cooled down, the final dimensions of the strip were measured and deformation ratios calculated.

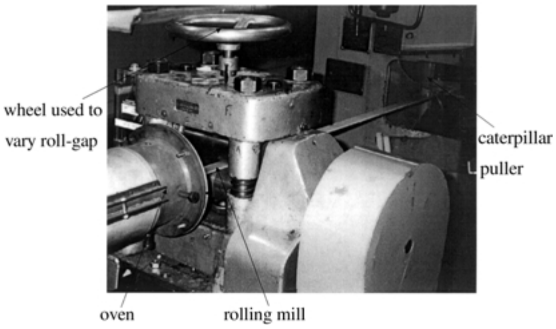

Figure 1 Photograph of a rolling mill.

The deformation or draw ratio of a material, λ, following solid phase processing, is defined as

$$\lambda = \frac{\text{final dimension}}{\text{initial dimension}}$$

and is used to determine the length, width and thickness draw ratios, i.e. λ_l, λ_w, and λ_t. The roll-drawn material was produced in the form of strips (see Figs 2 and 3) with a draw ratio of 1.6 in the length and 0.9 in the width (i.e. $\lambda_l \times \lambda_w = 1.6 \times 0.9$).

2.2. Method of crosslinking

The method used to crosslink polyethylene was to generate free radicals via gamma-irradiation which can either combine with other free radicals or undergo non-branching chain reactions with dissolved acetylene molecules resulting in the formation of crosslinks between the main polymer chains [5, 9]. For the purely crosslinked material block (approximately 70 × 70 × 70 mm) of UHMWPE RCH 1000 material was placed into a stainless steel cylinder at a temperature of 100 °C. A vacuum pump was used for 16 h to remove air from the cylinder and also any dissolved oxygen from the polyethylene, before acetylene was added under atmospheric pressure and still at a temperature of 100 °C. In order to ensure the polymer had absorbed sufficient acetylene, this process was extended over 31 h. The UHMWPE sample was then cooled to room temperature (ca. 18 °C) and gamma-irradiated with a dose of 2.5 MRad (2.5×10^4Gy) at Atomic Energy Authority (AEA) Harwell whilst still in the presence of the acetylene gas. Following irradiation, the UHMWPE was then annealed at 100 °C for 5 h, still in the acetylene gas atmosphere. This final annealing step ensured the reaction of any remaining free radicals.

The roll-drawn GUR 1120 material with draw ratios $\lambda_l \times \lambda_w = 1.6 \times 0.9$ was crosslinked using the same acetylene-enhanced process as described above.

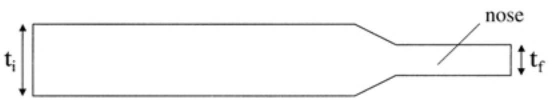

Figure 2 Longitudinal cross-sectional view of the billet used for roll-drawing, where t_i = initial thickness and t_f = final thickness.

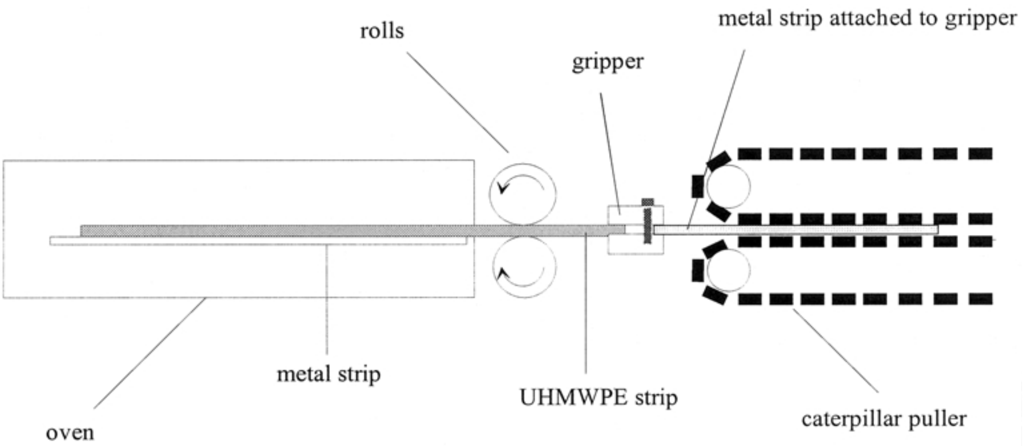

Figure 3 Schematic diagram of the roll-drawing rig.

2.3. Test specimens and wear counterfaces

The tensile specimens and wear pins (see Fig. 4 and Fig. 5, respectively) were machined from the acetylene-enhanced crosslinked RCH 1000, the roll-drawn GUR 1120 and acetylene-enhanced crosslinked roll-drawn GUR 1120 whilst the counterface plates and disk were made from cobalt chrome (CoCr) alloy (low carbon content). The surfaces of the smooth metal counterfaces were polished and lapped, giving the desired low surface roughness, R_a of 0.01 μm. The rough counterfaces were first polished and lapped and then roughened by a grinder to the R_a value of 0.09 μm. This initial polishing and lapping removed any background periodicity of the surface. The lubricant used in all the wear tests was a solution of 25% bovine calf serum and 75% of a deionised water solution containing 0.1% sodium azide.

3. Methods

3.1. Gel content analysis

Gel content analysis was conducted on the acetylene-enhanced crosslinked and acetylene-enhanced crosslinked roll-drawn samples, in order to estimate the degree of crosslinking. Samples of UHMWPE were placed in a weighed stainless steel gauze containers (120 gauge). Gel-fraction determinations were carried out as per the method of Kang *et al.* [6] with the exception that decahydronaphthalene (dekalin, boiling point = 192 °C) containing 2,6-di-*t*-butyl-*p*-cresol antioxidant (1% w/v) was used as the solvent. The residual soluble component (i.e. the non-crosslinked chains) of the irradiated polymer was extracted by immersing the sample in boiling dekalin containing 0.5–1% of 2,6-di-*t*-butyl-*p*-cresol as antioxidant. Since the samples were made of UHMWPE, with long entangled molecular chains due to the high molecular weight, they were solvent extracted in the dekalin solution for 96 h. Following solvent extraction, the samples were rinse-washed in boiling acetone (61 °C) and then dried in an oven at 100 °C for 12 h. The gel fraction was obtained by dividing the final sample weight by the initial weight and indicated the amount of crosslinking present in the sample.

3.2. X-ray analysis

Wide-angle X-ray diffraction (WAXD) of the purely roll-drawn UHMWPE and crosslinked roll-drawn UHMWPE was carried out in order to examine the degree of molecular orientation.

The 110, 200, 020 and 002 crystalline reflections were examined (where the last three reflections enabled a direct examination of *a*-, *b*- and *c*-axes) using two WAXD techniques; (i) photographic flat film, with Ni-filtered Cu radiation and (ii) a four-circle texture goniometer (Huber

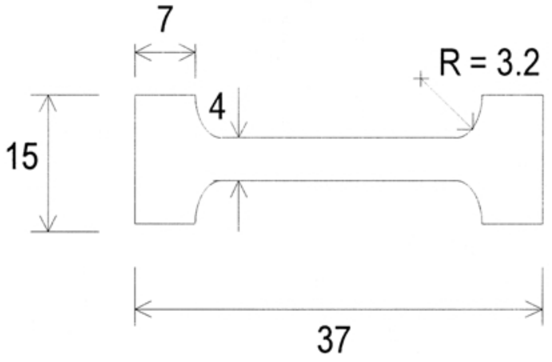

Figure 4 Tensile specimen. Thickness = 1.6 (dimensions in mm).

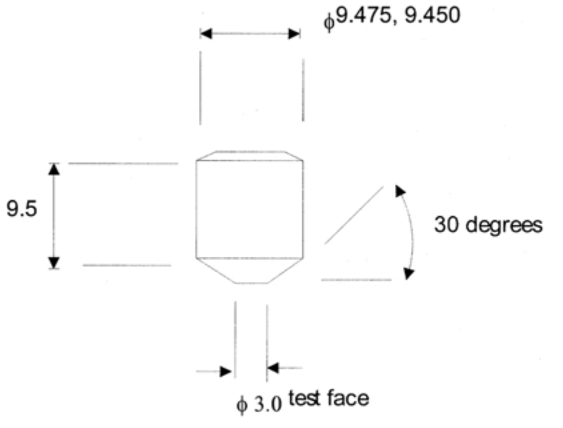

Figure 5 Wear pin dimension (in mm).

4020), with monochromatized Cu radiation. The former technique enables a quick examination of the orientation of most of the diffracting planes approximately parallel to the incident X-ray beam; the latter enables 2θ-scans to be performed, as well as a more quantitative measurement of the distribution of the diffracting plane normals in all directions with respect to the sample (pole figures). This method has been described in more detail by Chaffey *et al*. [7].

In order to make the appropriate WAXD measurements, samples were cut parallel to the *x*–*y* plane and normal to *z* (i.e. the compression axis – see Fig. 6), from the roll-drawn specimens. Samples had a length of 25 mm, width of 15 mm and a thickness of about 1 mm.

3.3. Tensile testing

Tensile specimens were taken from the surface of the roll-drawn and crosslinked roll-drawn products, parallel and perpendicular to the draw direction. All these materials were tensile tested in the form of flat dumbbells of 1.6 mm thickness (cut out from strips of UHMWPE machined from the appropriate plane) using a die-cutter. The dimensions of these specimens are shown in Fig. 4.

This dumbbell shape was chosen as it was the smallest available and the size of the roll-drawn and crosslinked roll-drawn polyethylene samples prevented the use of larger specimens. The change in width of the dumbbells at the grips was severe, and most of the specimens failed at the end of the narrow gauge section rather than in the gauge section itself. The width and thickness of the gauge section of each dumbbell was measured using a micrometer, so that the initial crosssectional area could be calculated. Tensile tests were carried out on a Howden universal testing machine at a separation rate of 180 mm/min and at room temperature and atmospheric pressure. Each dumbbell was pulled to failure, and the loads and crosshead displacements were recorded at set intervals of time (usually every 20 ms). At least seven specimens were tested for each material type. Since the deformation was homogeneous with no evidence of necking up to fracture, the true stresses and strains could be calculated from the following equations (assuming constant volume):

True strain: $\varepsilon_t = \ln(1 + \varepsilon_n)$

True stress: $\sigma_t = \sigma_n(1 + \varepsilon_n)$

where σ_t = true stress, σ_n = nominal stress, ε_t = true strain and ε_n = nominal strain.

The 5% proof stress, ultimate tensile stress (UTS), strain to failure, and energy to failure were calculated from the plots of true stress vs true strain created for each specimen. The yield stress was not calculated as it was believed that the 5% proof stress gave a better indication of the material properties.

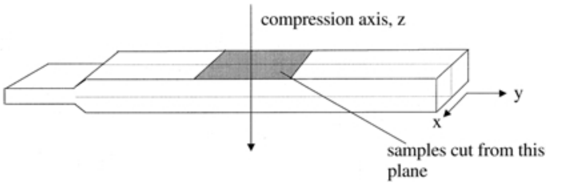

Figure 6 X-ray samples were cut from the *xy*-plane of the roll-drawn strips.

3.4. Wear testing

The wear properties of the purely crosslinked material has previously been compared using four different wear test configurations [2]: (i) unidirectional motion with a smooth counterface, (ii) multidirectional motion with a smooth counterface, (iii) unidirectional motion with a rough counterface and (iv) multidirectional motion with a rough counterface. In the present study, the roll-drawn and crosslinked roll-drawn materials were subjected to the unidirectional rough and multidirectional smooth tests only, as these were the two extreme configurations which gave the highest wear rates. Wear pins made from the roll-drawn and crosslinked roll-drawn materials were aligned so that the draw direction was parallel to the direction of sliding of the CoCr plate. A summary of the different tests carried out as part of this study is shown in Table I.

After each period of wear testing when the desired sliding distance had been reached, each set of test apparatus was dismantled and cleaned. The test pins were removed from the holders and cleaned ultrasonically along with the control pins to remove all traces of debris and lubricant. The pins were then placed in a controlled environment for 2 days after which they were carefully weighed using a Gallenkamp balance accurate to 1 μm. The weight changes of the unworn control pins were then either added or subtracted from the weight changes of the test pins to enable the weight loss due to wear of the test pins to be calculated. This was then converted to a volume loss and the corresponding wear factors were calculated using the following standard equation:

$$\text{Wear factor, } K\ (\text{mm}^3/\text{Nm}) = \frac{\text{Volume loss, } V\ (\text{mm}^3)}{\text{Load, } L\ (\text{N}) \times \text{Sliding distance, } X\ (\text{m})}$$

A Students' *t*-test was used to analyze the wear data as per the method documented by Mould [8]. Confidence limits of 95% were also calculated by multiplying together the standard error and the Students' *t*-value that were found for a set of data from one material [8]. These confidence limits were presented in the form of error bars on the wear factor histograms. Statistical significance between the mean wear factors of the two materials was determined using a Students' *t*-test for each test condition. The probability, *p*, was taken as the probability that the difference between the means occurred purely by chance. Significance was taken for $p < 0.05$.

TABLE I Summary of tensile and wear testing carried out on roll-drawn and crosslinked roll-drawn UHMWPE

Material	Tensile testing	Multidirectional smooth wear test	Unidirectional rough wear test
Roll-drawn	✓	✓	✓
Crosslinked roll-drawn	✓	✓	✓

4. Results

4.1. Gel fraction analysis

The crosslinked roll-drawn material yielded a gel fraction of 0.990, whereas the purely roll-drawn strip F9 gave a value of 0.091. Because of the presence of a finite gel fraction in the virgin non-crosslinked UHMWPE, it was not possible to directly calculate the degree of crosslinking. Instead, the true gel fraction ($\mathrm{Gel}_{\mathrm{true}}$) of the irradiated sample was estimated by simply subtracting the measured gel fraction of the purely roll-drawn material (Gel_r) from the measured gel fraction of the irradiated and roll-drawn material (Gel_{ir}):

$$\mathrm{Gel}_{\mathrm{true}} = \mathrm{Gel}_{ir} - \mathrm{Gel}_r$$

This yielded a $\mathrm{Gel}_{\mathrm{true}}$ value of 0.899 for the crosslinked roll-drawn GUR 1120, which indicated a slightly higher degree of crosslinking than the purely crosslinked UHMWPE which gave a $\mathrm{Gel}_{\mathrm{true}}$ value of 0.791 [2]. From these values the degree of crosslinking could be estimated. The work of Jones *et al.* [9] and especially Fig. 9 therein was used to estimate the total number of crosslinks present in the crosslinked roll-drawn GUR 1120. By reading values of this graphical figure for the gel fraction found for this crosslinked roll-drawn material, the ''gel-effective'' and ''total'' numbers of crosslinks were estimated to be 1.29 and 5.04 per pre-irradiated molecule with number average molecular weight, M_n, O, respectively. (''Gel-effective'' crosslinks are those which affect the gel or molecular weight.) According to previous work by the present authors [2], the ''gel-effective'' and total numbers of crosslinks were estimated to be 0.88 and 2.01 per pre-irradiated molecule with number average molecular weight, $M_n, 0$, respectively for the purely crosslinked UHMWPE [2]. Although the estimated number of ''gel-effective'' crosslinks was expectedly low, the estimated number of ''total'' crosslinks within the crosslinked roll-drawn GUR 1120 was five crosslinks per initial number average molecule as compared with only two for the purely crosslinked RCH 1000 [2]. These results indicated that an extensive network had developed in the roll-drawn UHMWPE GUR 1120 following gamma-irradiation and annealing in acetylene with an absorbed dose of 2.5×10^4 Gy(2.5×10^6 Rad).

4.2. X-ray diffraction

The purely roll-drawn material showed a uniplanar axial structure. As defined in Fig. 7 this uniplanar structure consisted of the *c*-axes oriented parallel to the draw direction, the *b*-axes aligned with the width direction and the *a*-axes oriented parallel to the compression direction (i.e. through the thickness of the strip).

It was seen that after crosslinking, uniplanar axial orientation of the roll-drawn polymer was still present and very similar to the original roll-drawn strip prior to crosslinking; with the *a*-axes tending to lie along the thickness direction of the strip, the *b*-axes along the width direction of the strip and the *c*-axes preferring the length direction. However, the degree of orientation of the *c*-axes was slightly lower in the crosslinked roll-drawn UHMWPE, suggesting that the high temperature used in the annealing process may have caused the molecules to initiate relaxation back to their original isotropic state.

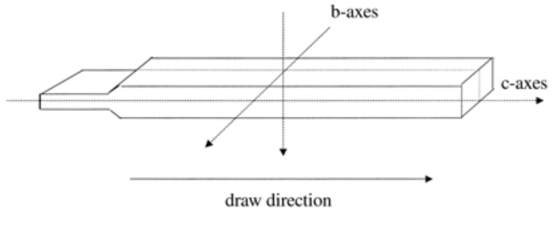

Figure 7 Orientation of axes of unit cell throughout strip post roll-drawing.

4.3. Tensile tests

It can be seen from Fig. 8 that the roll-drawn UHMWPE when tested in the direction parallel to draw had a greater yield stress and 5% proof stress as well as lower strain to failure and UTS than the virgin GUR 1120. These were unlike results generated when testing in the perpendicular direction. In this case the material showed a lower yield stress, 5% proof stress and UTS plus higher strain to failure than the virgin GUR 1120. Table II shows the mean true tensile results.

Fig. 9 shows that the crosslinked roll-drawn material when tested perpendicular to the draw direction had a lower strain to failure, 5% proof stress, UTS and energy to failure when compared to the original virgin material. Specimens tested parallel to the direction of draw also showed a decrease in all tensile properties apart from the 5% proof stress which showed a significant increase when compared to that for the virgin material. Mean true tensile properties and 95% confidence limits for this material can be seen in Table III.

4.4. Wear tests

In the unidirectional rough pin-on-disk test (see Fig. 10) the mean wear factor for the roll-drawn product was slightly lower than for the virgin GUR 1120. A Students' *t*-test also showed that the difference between the means was not significant to the 95% confidence level by yielding a value of 0.35 for *p*.

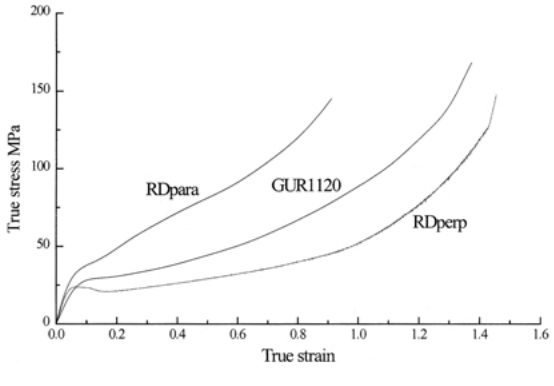

Figure 8 Graph of true stress vs true strain for roll-drawn strip ($\lambda_l \times \lambda_w = 1.6 \times 0.9$).

TABLE II Mean true tensile properties for the roll-drawn product ± 95% confidence limits ($\lambda_l \times \lambda_w = 1.6 \times 0.9$). *NS* = no significant difference with virgin material, *S* = significant difference with virgin material

Material	5% Proof stress MPa (to 2 d.p.)	UTS MPa (to 1 d.p.)	Extension to failure (to 2 d.p.)	Energy to failure MJ/m^3 (to 1 d.p.)
Roll-drawn GUR 1120 para to draw direction	33.7% ± 6.6 *S*	145.3% ± 9.7 *S*	0.91% ± 0.05 *S*	70.6% ± 5.6 *S*
Roll-drawn GUR 1120 perp to draw direction	23.2% ± 0.7 *S*	148.6% ± 20.7 *NS*	1.45% ± 0.04 *S*	70.3% ± 5.0 *S*
Virgin GUR 1120	28.3% ± 0.3	167.8% ± 6.1	1.37% ± 0.02	93.6% ± 2.7

TABLE III Mean true tensile properties for acetylene-enhanced crosslinked roll-drawn GUR 1120 strip ± 95% confidence limits ($\lambda_l \times \lambda_w = 1.6 \times 0.9$). *NS* = no significant difference with virgin material, *S* = significant difference with virgin material

Material	5% Proof stress, MPa (to 2 d.p.)	UTS MPa (to 1 d.p.)	Extension to failure (to 2 d.p.)	Energy to failure, MJ/m^3 (to 1 d.p.)
Crosslinked Roll-drawn GUR 1120 para to draw direction	32.2% ± 0.8 *S*	126.6% ± 6.8 *S*	0.86% ± 0.05 *S*	54.2% ± 4.6 *S*
Crosslinked Roll-drawn GUR 1120 perp to draw direction	27.4% ± 0.8 *NS*	113.6% ± 8.2 *S*	1.10% ± 0.04 *S*	53.7% ± 3.6 *S*
Virgin GUR 1120	28.3% ± 0.3	167.8% ± 6.1	1.37% ± 0.02	93.6% ± 2.7

For the multidirectional smooth pin-on-plate test (see Fig. 11) again there was no statistical difference in the mean wear factors (to the 95% confidence level) of the virgin GUR 1120 and roll-drawn product in the multidirectional smooth test. A Students' *t*-test confirmed this, as the probability p of the difference between the two materials occurring by chance was 0.68.

As can be seen in Fig. 12, the acetylene-enhanced crosslinked roll-drawn material wore 1.4 times more than the virgin material in the unidirectional rough pin-on-disk test. Statistical analysis using a Students' *t*-test gave a probability (p) of 0.08 that these mean results were different due to chance. Hence there was a significant difference between the wear resistance of these materials, but only at the 90% confidence level.

In the multidirectional smooth pin-on-disk test the crosslinked roll-drawn material wore 5.5 times less than the virgin material as can be seen in Fig. 13. A Student's *t*-test yielded a probability of $p < 0.001$ that these materials were different due to chance, and so these results were highly significant at above the 95% confidence level.

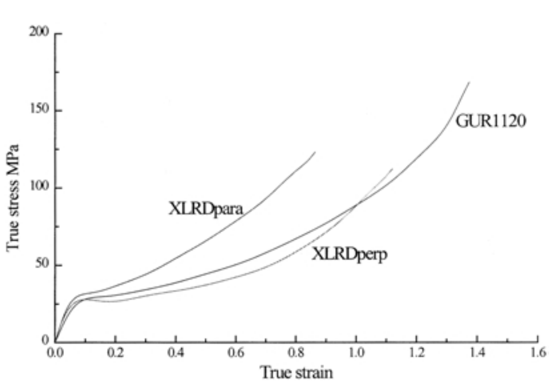

Figure 9 Graph of true stress vs true strain for acetylene-enhanced crosslinked roll-drawn GUR 1120 strip ($\lambda_l \times \lambda_w = 1.6 \times 0.9$).

5. Discussion

5.1. Effect of surface roughness and multidirectional motion

5.1.1. Roll-drawn GUR 1120 strip ($\lambda_l \times \lambda_w = 1.6 \times 0.9$)

Two different wear tests comprising unidirectional and multidirectional motion were carried out on roll-drawn strip F9. The multidirectional smooth and unidirectional rough tests subjected the material to a substantial amount of relative movement and surface roughness respectively. As can be seen in Fig. 14, the unidirectional rough test produced 2.3 and 2.0 times more wear for the virgin and roll-drawn material, respectively when compared to the multidirectional smooth test.

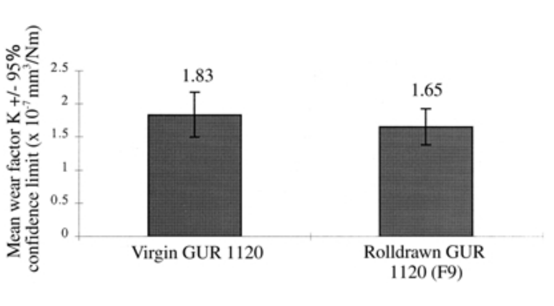

Figure 10 Mean wear factors of roll-drawn strip ($\lambda_l \times \lambda_w = 1.6 \times 0.9$) and virgin GUR 1120 for unidirectional pin-on-disk test (rough counterface) ± 95% confidence limits.

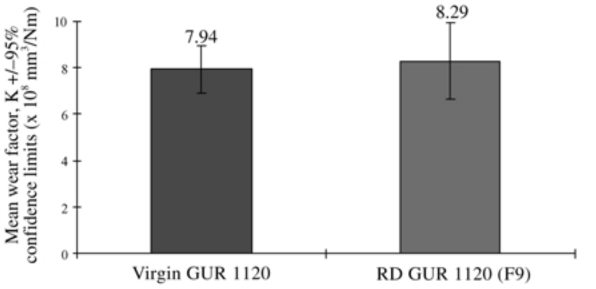

Figure 11 Mean wear factors of roll-drawn strip ($\lambda_l \times \lambda_w = 1.6 \times 0.9$) and virgin GUR 1120 for multidirectional pin-on-plate test (smooth counterface) ± 95% confidence limits.

Although there was no statistical difference to the 95% confidence level between the materials in either test, the roll-drawn material F9 showed 1.04 times more wear in the multidirectional test and 1.1 times less in the unidirectional test when compared to the virgin material. Therefore, the results suggest that a roll-drawn material may have benefits in a unidirectional test.

5.1.2. Crosslinked and roll-drawn UHMWPE

In the multidirectional smooth test (see Fig. 15), the crosslinked roll-drawn GUR 1120 yielded a wear factor that was five times less than its virgin equivalent ($p < 0.001$). In previous tests, purely crosslinked RCH 1000 material gave a wear factor that was 9.3 times less than the virgin RCH 1000 also with $p < 0.001$ Marrs *et al.* [2]. These results confirmed the benefits of crosslinking UHMWPE by using gamma-irradiation in the presence of acetylene gas for a multidirectional motion wear test with a smooth counterface.

In the case of the unidirectional rough test, the surface of the disc was much rougher than the plates in the multidirectional smooth test, causing an abrasive wear mechanism to take place. The asperities of the rougher disk removed material from the polymer pin via a ploughing action resulting in higher wear rates in this test than for the smooth test. The difference between the crosslinked roll-drawn and the virgin materials in the unidirectional test, although not statistically significant to 95% confidence limits ($p = 0.08$), mirrors the results from the same wear configuration for the purely crosslinked RCH 1000 [2]. In the latter case the crosslinking alone increased the wear rate of the polyethylene, and was statistically significant ($p = 0.05$).

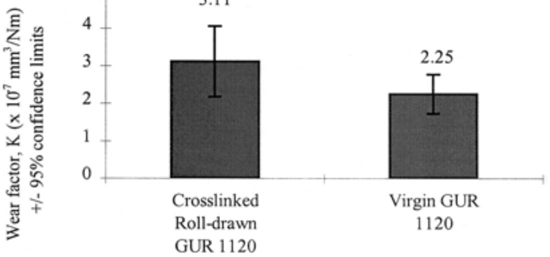

Figure 12 Mean wear factors for unidirectional pin-on-disk test (rough counterface) ± 95% confidence limits.

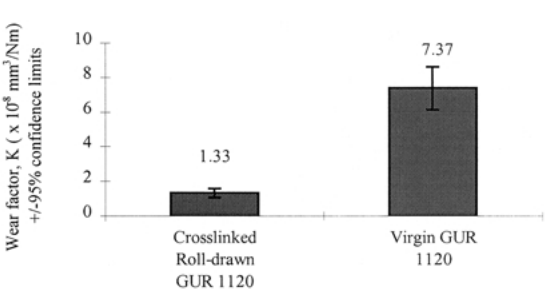

Figure 13 Mean wear factors for multidirectional pin-on-plate test (smooth counterface) ± 95% confidence limits.

5.2. Effect of roll-drawing followed by crosslinking

It is evident from previous work carried out by the authors that UHMWPE RCH 1000 crosslinked using gamma-irradiation in the presence of acetylene greatly reduced the wear in a smooth multidirectional motion test when compared with the virgin material [2]. These benefits were not present in a simple unidirectional motion test using a smooth counterface. This is of great clinical significance as the motion of the multidirectional test is closer to the relative motion in the hip than the standard unidirectional test. However, in both uni- and multidirectional tests against a rough counterface, there was little difference in wear rates between the virgin and the crosslinked material. This indicated that if the critically-smooth counterface of a prosthesis becomes roughened, e.g. due to third body damage, the benefits of crosslinking the material would be lost.

By crosslinking roll-drawn UHMWPE it was hoped that it would demonstrate lower wear factors when compared to the original virgin material in both the unidirectional rough and multidirectional smooth tests. However, it appears that the crosslinking process has lessened the benefits of the roll-drawing process. These benefits were lower wear rates in the unidirectional rough tests ($p = 0.4$). The present study did not demonstrate that a combination of roll-drawing and crosslinking yields benefits in a unidirectional rough test. This could be attributed to the network of crosslinks dominating over the uniplanar-axial orientation due to the strength and frequency of the links produced. It is also possible that the amount of uniplanar axial orientation of the roll-drawn material was lessened as a result of the relatively high temperature annealing process following crosslinking. In order to discover which of these two factors is

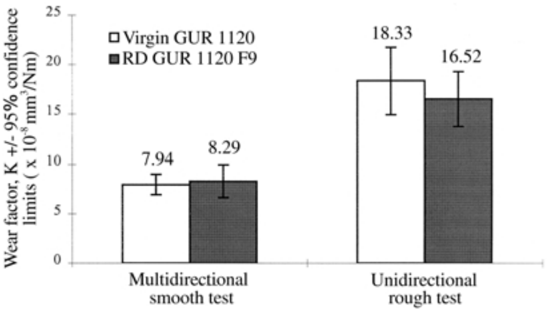

Figure 14 Comparison of mean wear factors for roll-drawn GUR 1120 strip ($\lambda_l \times \lambda_w = 1.6 \times 0.9$) and virgin GUR 1120 for two different wear conditions ± 95% confidence limits.

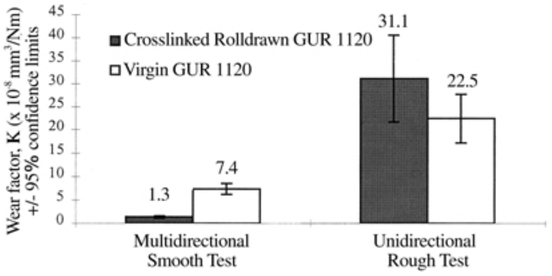

Figure 15 Comparison of mean wear factors for acetylene-enhanced crosslinked roll-drawn GUR 1120 strip ($\lambda_l \times \lambda_w = 1.6 \times 0.9$).

to be blamed for the loss of orientation (if indeed this is the case), it would be of benefit to roll-draw material after crosslinking so as to eliminate annealing as a possible source of relaxation.

6. Conclusion

It is clear from the present study that crosslinking UHMWPE in the presence of acetylene gas after roll-drawing provided great benefits in a multidirectional smooth test, but that these benefits were lost in a unidirectional rough test. These results support the previous finding by the authors that acetylene-enhanced crosslinking may show benefits for a total hip replacement, but only where the femoral head remains smooth. It is suggested that further work needs to be carried out using rough or scratched counterfaces with crosslinked materials that have been subsequently roll-drawn.

Acknowledgments

H. Marrs received an EPSRC CASE studentship that was supported by Stryker Howmedica Osteonics.

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Received October 12 1999
and accepted May 8 2000