The monotonic and cyclic fatigue behaviors of a conventional and a sequentially annealed highly crosslinked UHMWPE in a notch-induced triaxial stress-state

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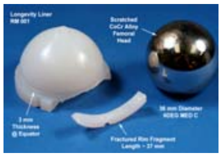
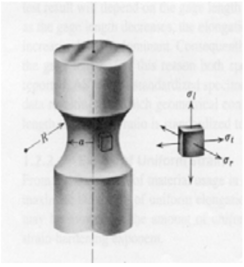
Global Goals

- Model the stress-strain behavior of UHMWPE in complex geometries and loading states
    - Via a constitutive model (Hybrid Model) employed in finite element models
- Predict static and cyclic fracture resistance of UHMWPE TJR components



Multiaxial Loading and “Notch Strengthening”

- UHMWPE bearing components of TJR’s have stress concentrations in the form of undercuts, sharp corners, rims, fillets, etc
- When dealing with notches in a ductile material, such as UHMWPE, a phenomenon known as “notch strengthening” may occur
    - Axial yield stress of the notched specimen is greater than that of the smooth specimen due to local triaxial stress state



Hertzberg, R.W., *Deformation and fracture mechanics of engineering materials.* 1989

Goals of this Study

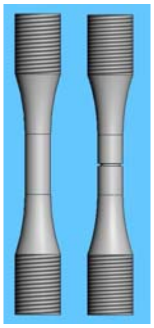
- For a sequentially annealed highly crosslinked and a conventional UHMWPE, examine the effects of notching and rate on:
  - The axial true stress-true strain behavior
  - Fracture micromechanism
  - Crystallinity and the lamellar thickness distribution upon deformation

Materials

- Prepared from extruded GUR 1050 barstock
- Sequentially Annealed (SA)
  - 3 Successive treatments
    - Irradiated at 30 kGy
    - Annealed at 130ºC for 8 hours
- Conventional Gamma Radiation Sterilized (30kGy)
  - Packaged in N_2
  - Irradiated at 30 kGy

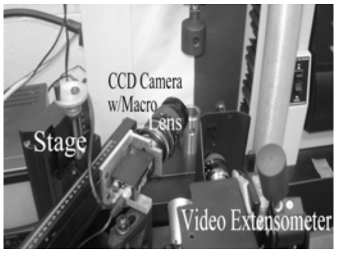
Monotonic Tension

- Cylindrical tensile specimens were tested in tension using an Instron 4411 electromechanical load frame in an environmental chamber at 37ºC
  - 2 geometries
    - Smooth (no notch, 8mm diameter)
    - Notched (0.45 mm radius, 8mm OD, 6mm ID)
  - 2 Rates
    - 30 mm/min
    - 150 mm/min
  - ~15 specimens×2 materials ×2 geometries×2 rates
    - ~120 specimens
  - Specimens were first soaked for 6 weeks in a PBS bath at 37ºC

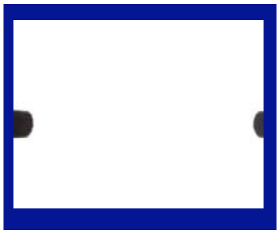


Monotonic Tension

- Smooth Specimens
  - Load and strain data were acquired using LabView and an Instron non-contacting video extensometer
- Notched Specimens
  - Load was acquired via LabView
  - Strain was found using video of the notched region acquired by a CCD camera with a macro lens mounted on a moving stage



Notch Deformation Behavior



Notch Strengthening and Hardening Ratios

$$\varphi_{\sigma or \varepsilon} = \frac{X_y}{X_{y,smooth}}$$

φ is the notch strengthening ratio

$$\psi_{\sigma or \varepsilon} = \frac{X_u}{X_y}$$

ψ is the hardening ratio

ANOVA: Mechanical Properties

$$X = \mu + \alpha[Material] + \delta[Notch] + \gamma[Rate] + \beta[Material : Notch] + \kappa[Material : Rate] + \lambda[Notch : Rate]$$

- X=
  - True axial yield stress or strain
  - True axial ultimate stress or strain
  - Stress- or strain-based notch strengthening ratio
  - Stress- or strain-based hardening ratio
- Material
  - 30kGy or SA
- Notch
  - Smooth or notched
- Rate
  - 30 or 150 mm/min

Differential Scanning Calorimetry

- Mettler-Toledo 823e DSC
- Crystallinity*
  - Five ~5mg specimens cut at the fracture plane using a clean razor blade for each condition plus the undeformed/control condition for both materials
  - Thermal sequence:
    - 1) Hold at 25ºC until stabilized
    - 2) Heat from 25 to 180 ºC at 10 ºC/min
- Lamellar Thickness Probability Density Functions**
  - One ~10mg specimen cut using a clean razor blade for each condition plus the undeformed/control condition for both materials
  - Thermal sequence:
    - 1) Hold at 50 ºC until stabilized
    - 2) Heat from 50 to 175 ºC at 1 ºC/min

*Spiegelberg, S., *The UHMWPE Handbook;* S.M. Kurtz, Editor. 2004, pp. 262
**Crist and Mirabella, J. Polymer Science B: Polymer Physics 1999, vol. 37, pp. 3131

Lamellar Thickness Distribution

$$l(T) = \frac{2\sigma_e}{\Delta H_f}\frac{T_m^o}{(T_m^o - T)}$$

- *l*(T) = lamellar thickness melting at T
- σ_e = (93 ± 8) mJ/m^2 - fold surface energy
- ΔH_f = 296 kJ/kg - heat of fusion of PE crystal
- T_m^o = 145.8 ºC - equilibrium melting T
- T = Melt Temperature

$$g(T) = \frac{\rho_c P(T)(T_m^o - T)^2}{2\sigma_e T_m^o M \alpha_m \left(\frac{dT}{dt}\right)}$$

- g(T) = weight fraction of crystals melting at T
- P(T) = DSC Heat Flow curve
- dT/dt = heating rate 1K/min
- M = mass of sample
- α_m = mass fraction of crystals that melt

Crist and Mirabella, J. Polymer Science B: Polymer Physics 1999, vol. 37, 3131

ANOVA: Crystallinity

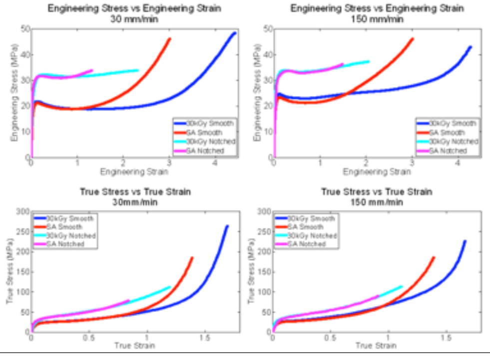
$$X = \mu + \alpha[Material] + \delta[Deformation] + \gamma[Rate] + \beta[Material : Deformation] + \kappa[Material : Rate] + \lambda[Deformation : Rate]$$

- X=Crystallinity
- Material
  - 30kGy or SA
- Deformation
  - None (control), smooth, notched
- Rate
  - 0,30,150 mm/min

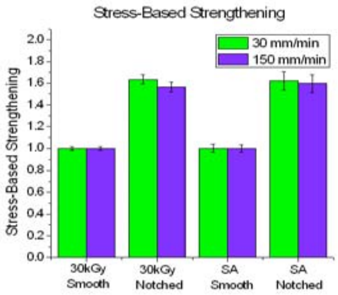
Stereomicroscopy and Scanning Electron Microscopy

- Fracture surfaces were examined from all specimens
  - Sputter coated with palladium
  - Examined with stereomicroscope
- Representative specimens were examined in a Hitachi S-4500 SEM at 5kV

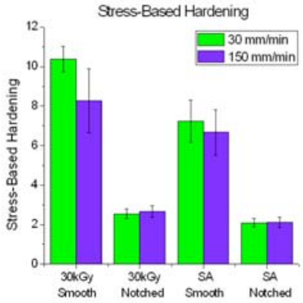
Stress-Strain



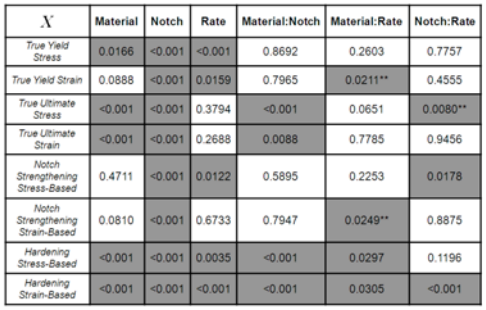
Notch Strengthening Ratio



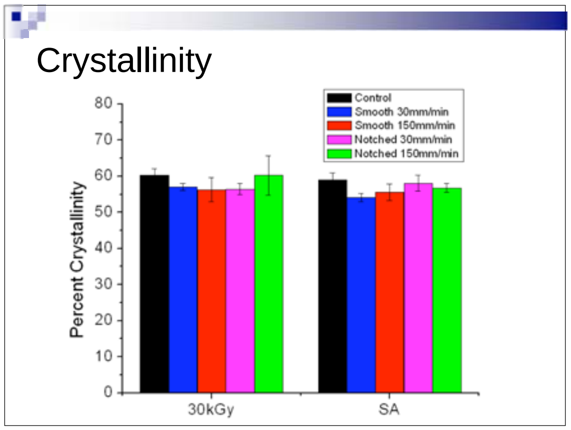
Hardening Ratio



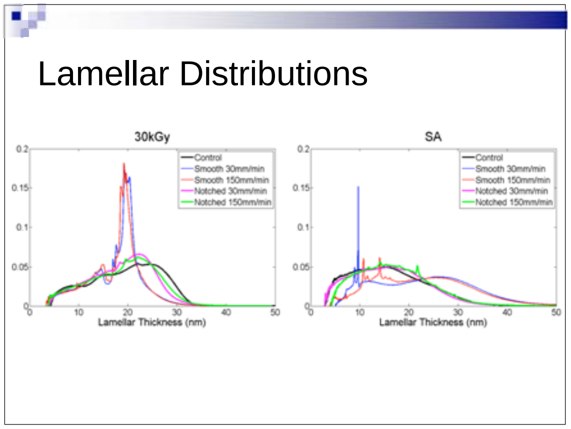
ANOVA - Notching affected all parameters; material and rate differences as well



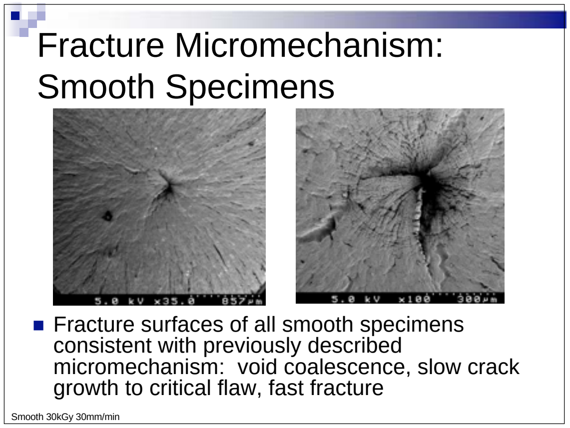
X	Material	Notch	Rate	Material:Notch	Material:Rate	Notch:Rate
True Yield Stress	0.0166	<0.001	<0.001	0.8692	0.2603	0.7757
True Yield Strain	0.0888	<0.001	0.0159	0.7965	0.0211**	0.4555
True Ultimate Stress	<0.001	<0.001	0.3794	<0.001	0.0651	0.0080**
True Ultimate Strain	<0.001	<0.001	0.2688	0.0088	0.7785	0.9456
Notch Strengthening Stress-Based	0.4711	<0.001	0.0122	0.5895	0.2253	0.0178
Notch Strengthening Strain-Based	0.0810	<0.001	0.6733	0.7947	0.0249**	0.8875
Hardening Stress-Based	<0.001	<0.001	0.0035	<0.001	0.0297	0.1196
Hardening Strain-Based	<0.001	<0.001	<0.001	<0.001	0.0305	<0.001



Crystallinity



Lamellar Distributions

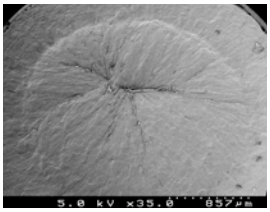


Fracture Micromechanism: Smooth Specimens

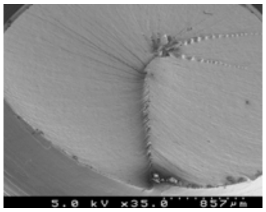
- Fracture surfaces of all smooth specimens consistent with previously described micromechanism: void coalescence, slow crack growth to critical flaw, fast fracture

Smooth 30kGy 30mm/min

Fracture Micromechanism(s): Notched Specimens: Two Zone or One Zone

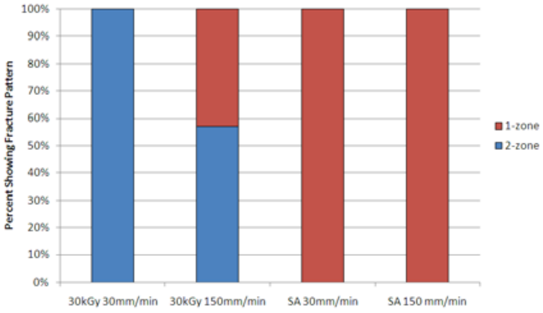


Notched 30kGy 30mm/min



Notched SA 30mm/min

Notched Specimen Fracture



Observations

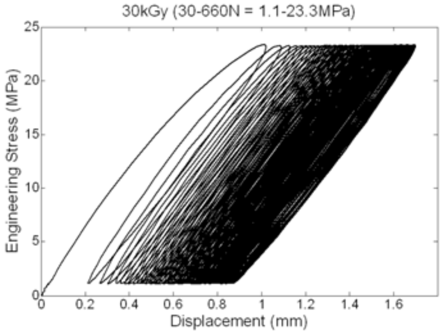
- Both materials showed comparable notch strengthening; crosslinking does not appear to prohibit this behavior*
- The observed strengthening for both UHMWPE materials suggests that the triaxial stress state inhibits crystalline lamellar deformation mechanisms - supported by lamellar distribution findings
- The triaxial (notched) stress state reduced orientation hardening in the amorphous phase*
- The observed 2-zone vs 1-zone fracture patterns of the notched specimens may be indicative of differences in more ductile vs. more brittle behavior between the SA and 30kGy materials

*Sobieraj, et al. Biomaterials, 26 (2005), 3411-26

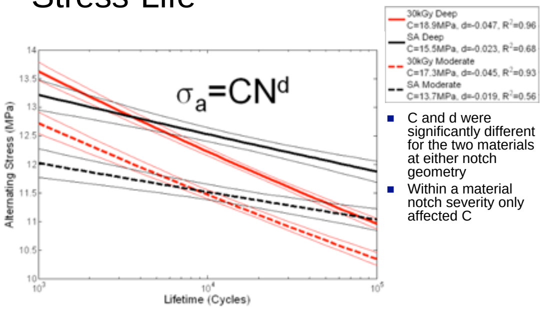
Notched S-N fatigue testing

- Two circumferentially grooved tensile specimen geometries
  - ☐ OD = 8mm, ID = 6mm
  - ☐ Moderate: notch radius = 0.9mm, k_t = 2.1
  - ☐ Deep: notch radius = 0.45mm, k_t = 2.7
- Specimens were presoaked for 12 weeks in a PBS bath at 37ºC.
- Fatigue testing to failure was performed in a PBS bath at 37ºC on an Instron 8511 load frame
  - ☐ 2Hz sinusoidal wave (Tension-tension loading, R ≤ 0.05)
- The intention was to capture lifetimes in the low-to-intermediate (1,000-100,000) cycle range
- Stress-Life Curves were found ($\sigma_a = CN^d$)
- Seven to eight stress levels were evaluated for each material/geometry condition (n = 1-6 specimens per stress level)

Cyclic Load-Displacement



Stress-Life



$$\sigma_a = CN^d$$

- C and d were significantly different for the two materials at either notch geometry
- Within a material notch severity only affected C

σ_a = cyclic axial stress amplitude in the notch

Observations/Comments

- Notched specimens can be tested to fracture to establish S-N behavior
- The advantage of this approach is
  - testing can be taken to fracture with stresses below the monotonic yield stress
  - the necking phenomena, drawing, and orientation hardening of a specimen that occurs in smooth specimens can be avoided

Observations/Comments

- The results of this study will be used to incorporate fatigue life into the Hybrid constitutive model for UHMWPE
- While axial cyclic stress amplitudes have thus far been determined, comparison of the effective cyclic stress amplitudes (due to the triaxial stress state in the notch) need to also be determined
- Caution should be taken when interpreting these findings to-date with respect to prediction of the performance of UHMWPE total joint replacement components
  - Crosslinking is detrimental to fatigue crack *propagation* resistance
  - High-cycle fatigue resistance was not examined in this study

Acknowledgements

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