CASE
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On Mechanical Properties of UHMWPE

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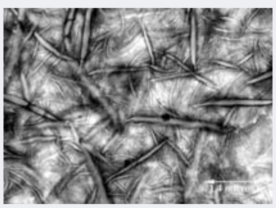
Ultra high molecular weight polyethylene: > 40 years in clinical use in joint replacements



MW > 2 million
% crystallinity ≥ 55%

Crystalline lamellae 10-40nm thick

$-[CH_2-CH_2]-_n$

Orthopaedic Basic Science | American Academy of Orthopaedic Surgeons

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Material factors that influence mechanical performance: wear and fracture resistance

UHMWPE resin
- Different Molecular weight's, MW distributions, % crystallinities, lamellar sizes, additives (e.g., calcium stearate or not)

Manufacturing and processing methods
- Ram extrusion, compression molding to sheet, compression molding to final product

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Major UHMWPE resins in medical use

Resin	Mfg.	MW	% Cryst.
1020/1120	Ticona	4 million	60
1050/1150	Ticona	6 million	58
1900	Himont	2-4 million	75

Material factors that influence mechanical performance: wear and fracture resistance

Sterilization method

Gamma radiation (oxygen or inert gas environment), ethylene oxide gas, gas plasma

Microstructural modifications

Crosslinking

Gamma radiation in air

Common method of sterilization from late 1970's to mid-1990's

25 to 40 KGy dose

Fast, economical, reliable

Kurtz, The UHMWPE Handbook

Gamma radiation sterilization in air of UHMWPE is *not* a benign process

Events:

1) Chain scission / recombination

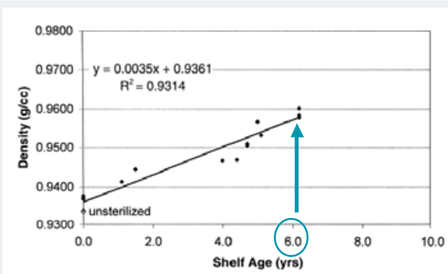
2) Crosslinking - will predominate in absence of O_2

3) Oxidation – will predominate in presence of O_2

Dissolved oxygen is abundant in the amorphous regions; components fully saturated prior to sterilization

Reaction with oxygen continues following sterilization

Post-irradiation aging (oxidation) of UHMWPE occurs for *years*



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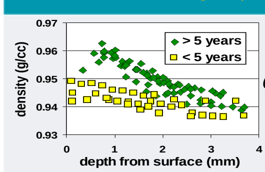
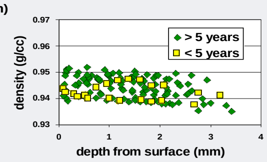
Aging is UHMWPE inhomogeneous and resin/manufacturing dependent

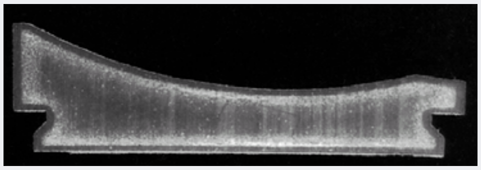


MG II tibial knee insert
GUR 415 resin/ram extruded

MG I tibial knee insert
Himont resin/molded



Physical evidence of inhomogeneous oxidative embrittlement of UHMWPE



Maximum oxidation is often 1-2 mm *below* the articulating surface (the “white band”)

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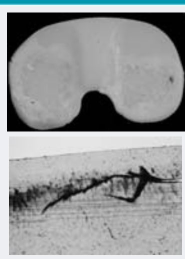
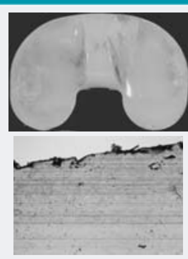
Cracks grow through subsurface embrittled material



Subsurface oxidation peak



No subsurface oxidation peak

Won et al, CORR, 2000

Consequences of post-irradiation aging of UHMWPE

Physical/chemical:

↓ MW ↑ % crystallinity

↑density ↑oxidation

Mechanical:

↑ elastic modulus ↓ ductility

↓ fatigue resistance ↓ wear resistance

Structural:

↓ contact area ↑stresses on components

Subsurface oxidation is the primary factor affecting delamination of UHMWPE components

Embrittled subsurface layer has poor crack resistance

Oxidation during shelf-aging (prior to implantation) – can compromise in vivo performance of a UHMWPE component

Contemporary sterilization methods of UHMWPE 1998 →

- Gamma radiation sterilization in the absence of oxygen (nitrogen, argon, vacuum packaging)
- Post-processing methods (remelting or annealing) to extinguish/reduce radicals and inhibit post-irradiation aging
- Alternative non-ionizing sterilization methods (e.g., gas plasma, ethylene oxide gas)
- *Other more recent modifications include vitamin-E doping to reduce free radicals

Kurtz, The UHMWPE Handbook

In vivo degradation of UHMWPE components

Does in vivo oxidation occur in the absence of significant shelf aging?

How much do the chemical and/or mechanical properties of UHMWPE liners change after implantation?

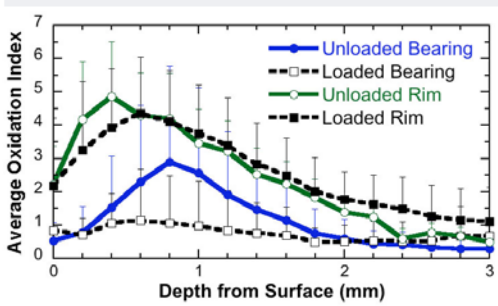
What is the clinical significance (if any) of in vivo oxidation?

Kurtz, et al., *JBJS*, Vol. 87, 2005

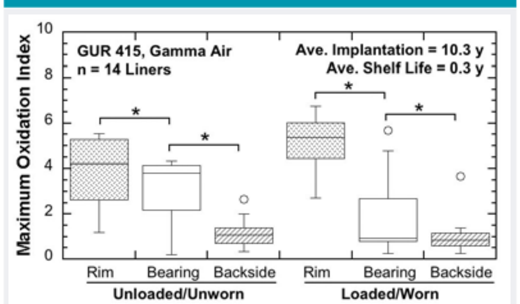
Examined retrieved hip cups, one resin (GUR 415), gamma sterilized air – short shelf lives

Fourteen modular cementless acetabular liners
Revised: average of 10.3 years (5.9 to13.5 years)
Average shelf life: 0.3 years (0.0 to 0.8 year)

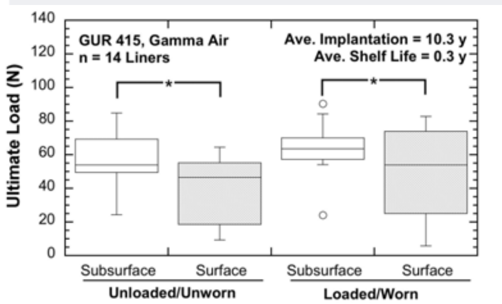
In Vivo Oxidation distribution with depth and location



In vivo oxidation: Rim had highest Oxidation Index



In vivo oxidation: ultimate load varies by location (small punch test)



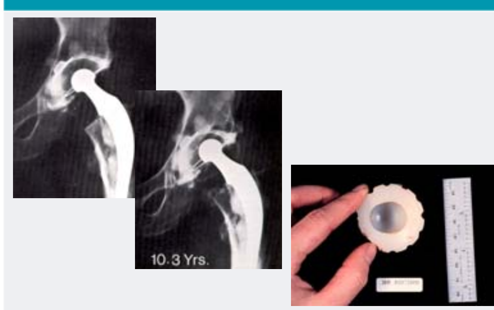
In vivo oxidative degradation

In vivo oxidative degradation *does* occur

Exposed regions (unloaded) and thinner regions (rims) more degraded than protected/thicker regions

Hypothesis: Exposed/thinner regions – more access to oxygenated body fluids

Abrasive/adhesive wear limits the lifetime of THR's



Crosslinking of UHMWPE to reduce wear

In late-1990's, investigators began to re-explore crosslinking of UHMWPE using radiation (gamma or e-beam) or chemical (peroxide) approaches

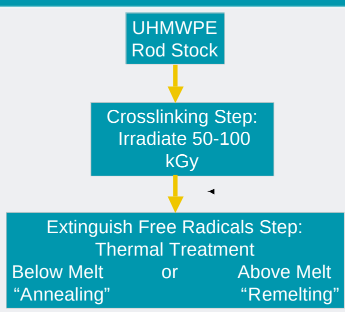
- 50 to 100 Kgy

Crosslinking leads to reduced adhesive/abrasive wear

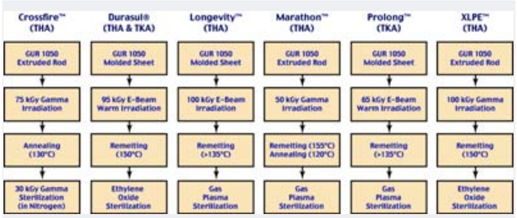
First attempted in 1970s in Japan by Oonishi using 1000 KGy; Grobbelaar in South Africa using 100 KGy

Oonishi et al, Rad Phys Chem, 1992
Grobbelaar et al, JBJS(B), 1978

Contemporary 1st generation crosslinked & thermally treated UHMWPE's



First generation crosslinked UHMWPEs for orthopaedic implants

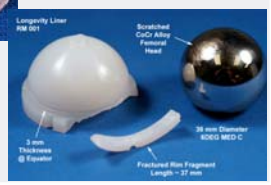


Kurtz, The UHMWPE Handbook

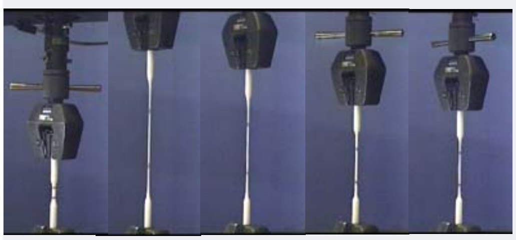
In addition to wear, fracture is a concern

Conventional

Crosslinked



Crosslinking of UHMWPE alters mechanical properties



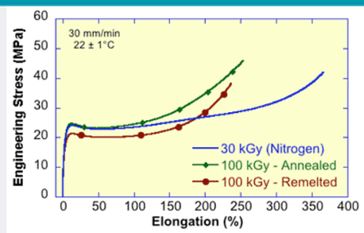
Undeformed	Virgin (Control)	30 kGy N_2	100 kGy Anneal	100 kGy Remelt

Kurtz, Rimnac et al, Biomaterials, 2002

Effect of crosslinking and annealing/remelting on physical properties

Group	Radiat. Environ.	Post-processing	Density g/cc	% Xtal	T_m, C
30 kGy (sterilized)	N_2	None	0.933	51.3	138.5
100kGy (annealed)	Air	110C/2hr	0.934	60.8	141.6
100kGy (remelted)	Air	150C/2hr	0.927	45.7	137.5

Effect of crosslinking on stress vs. strain behavior

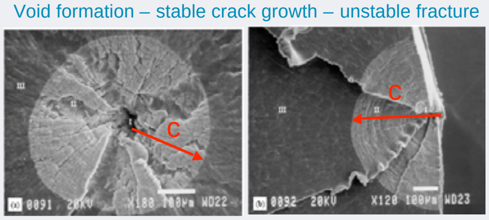


Reduced ductility (annealed and remelted);
Reduced yield and ultimate strength (remelted)

Kurtz, Rimnac et al, Biomaterials, 2002

Failure micromechanism

Void formation – stable crack growth – unstable fracture

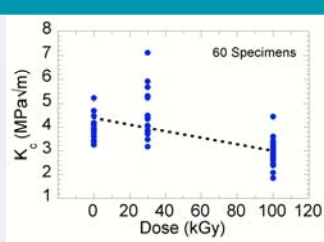


Estimate fracture toughness:

$K_c = F\sigma(\pi c)^{0.5}$

Gencur, Rimnac, et al, Biomaterials, 2003

Effect of crosslinking on resistance to fracture

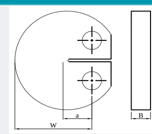


Fracture toughness reduced by crosslinking

Gencur, Rimnac, et al, Biomaterials, 2003

What is the effect of crosslinking and envinronment on fatigue crack propagation resistance?

Sterilized (30kGy, N_2)
Annealed (100 kGy, 130°C)
Remelted (100 kGy, 150°C)



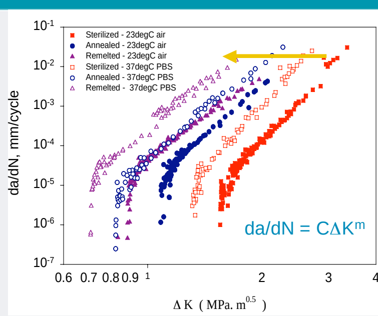
Ambient air

Phosphate buffered saline (PBS) bath at 37°C.

Specimens tested in the PBS bath were first soaked in PBS at 37°C for 2 to 4 weeks.

Varadarajan, Rimnac, Trans. ORS, 2006

Fatigue crack propagation resistance reduced by crosslinking and 37C PBS environment



Sterilized vs. Annealed/Remelted

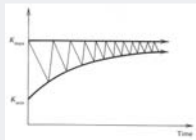
	Sterilized (30KGy)		Annealed (100KGy, 130°C)		Remelted (100KGy, 150°C)	
	23°C air	*37°C PBS*	*23°C air*	*37°C PBS*	*23°C air*	*37°C PBS*
m	9.48	10.85	8.22	7.82	6.87	7.21
C	1.87×10^{-7}	6.02×10^{-7}	1.06×10^{-5}	5.47×10^{-5}	5.14×10^{-5}	3.22×10^{-4}
$\Delta K_{inception}$	1.59	1.32	1.12	0.86	0.91	0.71

Crosslinked materials vs. Sterilized:
Lower m, higher C ΔK_{incep} ↓ 30%-45%

37°C PBS bath vs. air:
Higher C; ΔK_{incep} ↓17 to 23%
Difference is attributed to thermal softening
Similar observations by *Baker et al 2000* for non-sterile GUR4150HP tested in a 37°C de-ionized water bath (9% ↓ ΔK_{incep})

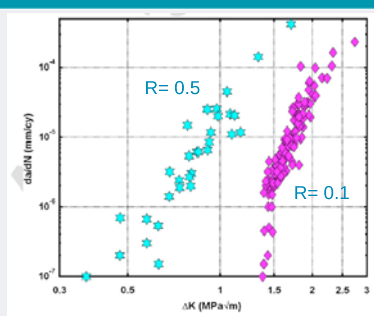
Peak Stress Intensity Dictates FCP in UHMWPE
Furmanski and Pruitt, Polymer June 2007

- GUR 1050, compression molded, thermally annealed
- Fatigue crack propagation tests conducted under three different R-ratio (P_{min}/P_{max}) scenarios:
  - constant R = 0.1*
  - constant R = 0.5
  - constant K_{max} (R variable, from 0.1 to 0.9):

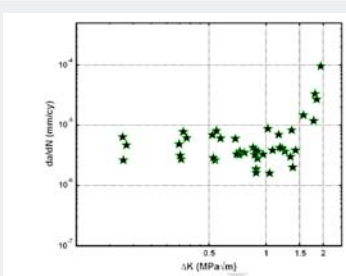


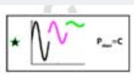
*FCP tests of UHMWPE primarily conducted in this manner

FCP ↓ as R-ratio increases: ΔK_{incept}, "threshold is lost"

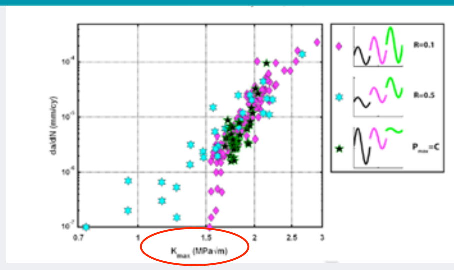


K_{max} constant: lower ΔK (higher R) approaches asymptote



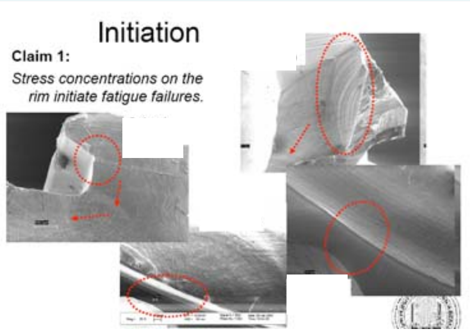


Peak Stress controls FCP behavior



Implication: stable crack growth can occur in the absence of cyclic loading - creep/brittle behavior

Initiation and growth of fatigue cracks in highly crosslinked UHMWPEs in vivo has a brittle appearance - images courtesy L. Pruitt



Recommendation:
Fatigue crack propagation of UHMWPE behavior too complex to reduce to a single value for comparison between materials (e.g., ΔK_{incep})

S-N behavior: Medel, et al., JBMR, 2007

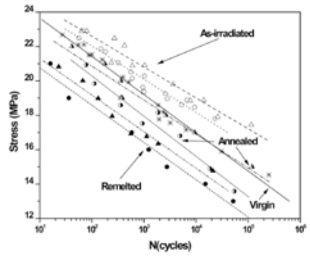
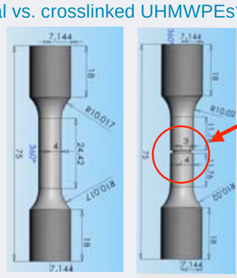


Figure 4. Stress–life curves for NI, (∗); β50, (○); and β150, (△) materials according to,[23] β50R, (●) and β150R, (▲), as presented in,[13] and β50A, (◑) and β150A, (◭), obtained in this work.

Failure:
strain = 0.12

Effect of crosslinking on notch sensitivity - mild notch risers

What is the monotonic notch sensitivity of conventional vs. crosslinked UHMWPEs?

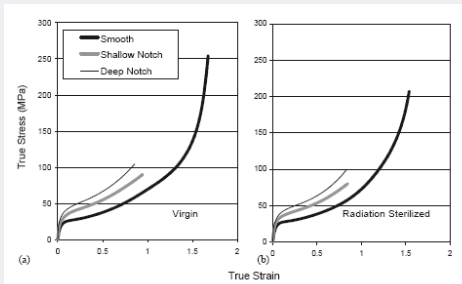


Sobieraj, Rimnac, et al., Biomaterials, 2005

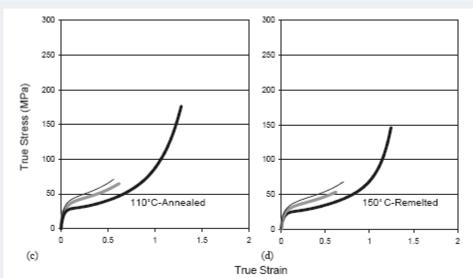
Video-based method used to track diametral strain in notch, determine true stress/strain

Prior to elongation   During elongation

Effect of notch on true stress / true strain



Effect of notch on true stress / true strain



Notch Strengthening and Hardening Ratios

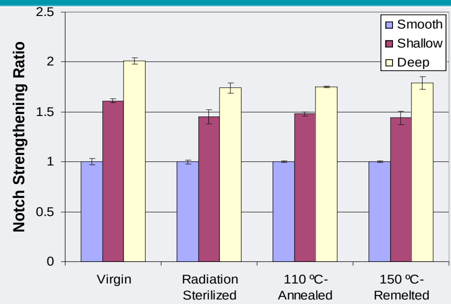
Notch strengthening ratio:

$$\varphi_{\sigma or \varepsilon} = \frac{\overline{X}_y}{\overline{X}_{y,smooth}}$$

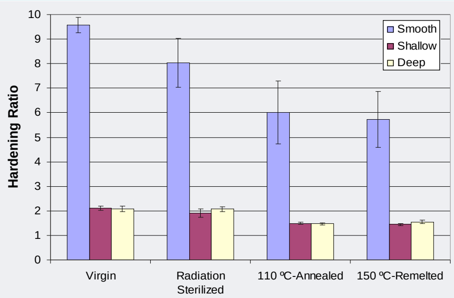
Hardening ratio:

$$\psi_{\sigma or \varepsilon} = \frac{\overline{X}_u}{\overline{X}_y}$$

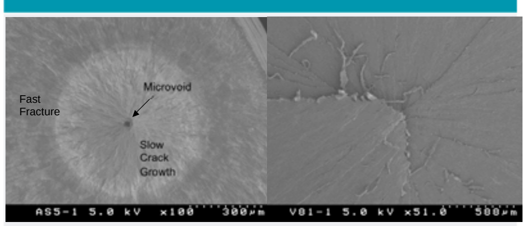
Notch strengthening ratio



Hardening ratio



Fracture micromechanisms

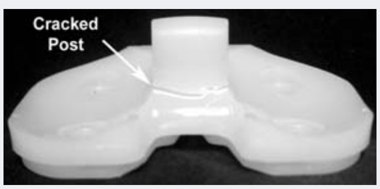


Un-notched Notched

Notch sensitivity

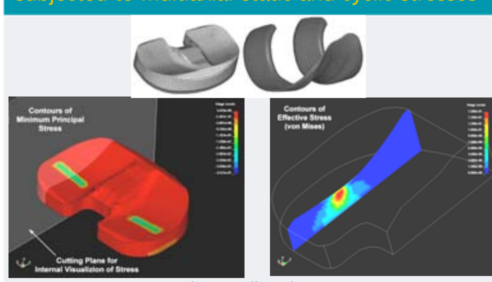
Crosslinked UHMWPEs are somewhat more sensitive to structural notches than conventional (virgin, radiation sterilized) UHMWPEs

Can we predict when static or cyclic fracture will occur?



In vitro fracture under cyclic loading

UHMWPE joint replacement components are subjected to multiaxial static and cyclic stresses



How accurate are the predicted stress and strain distributions?

Giddings et al. *J. Tribology*, 2001

Possible Material Models

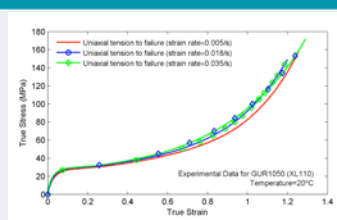
- Linear Viscoelasticity
- Metal Plasticity
- Arruda-Boyce model
- Hasan-Boyce model
- Bergstrom-Boyce model

None of these models work well for UHMWPE


Biomaterials

Constitutive modeling of ultra-high molecular weight polyethylene under large-deformation and cyclic loading conditions

Uniaxial Tension to Failure



The material response is characterized by linear elastic behavior, distributed yielding, and non-linear hardening

The material response is non-linear and rate-dependent

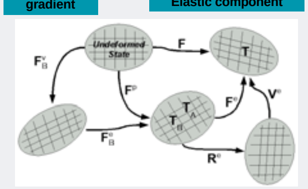
Hybrid Model - Kinematics

$$\mathbf{F} = \mathbf{F}^e \mathbf{F}^p$$

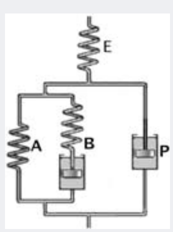
Deformation gradient

Elastic component

Viscoplastic component

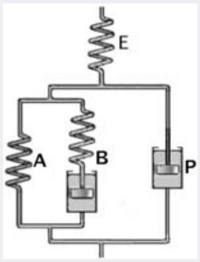


Deformation map



Rheological Representation

Hybrid Model



E - Linear elastic behavior

A - Equilibrium portion of backstress network
- Hyperelastic (8-chain model)
  - chain stretch

B - Viscoplastic portion of backstress network
- Hyperelastic (8-chain model)
  - chain stretch, distributed yielding
- Viscoplastic flow

P - Viscoplastic flow (crystalline regions)

Procedure

1) Calibrate models to available uniaxial data (monotonic testing at different strain rates and cyclic testing)
2) Simulate equibiaxial small punch and notched (triaxial) tensile tests using the calibrated models

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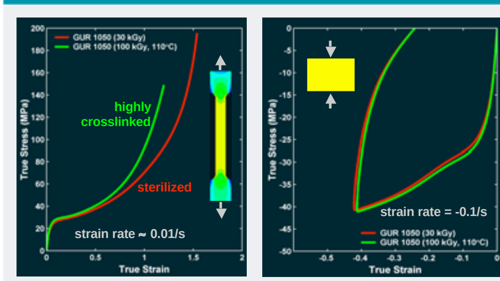
1) Calibrate model using properties obtained under tensile or compressive loading



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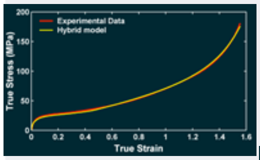
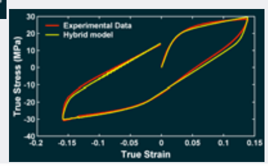
The model works for conventional and crosslinked UHMWPE formulations - uniaxial

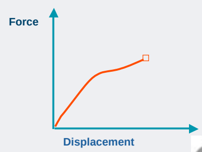


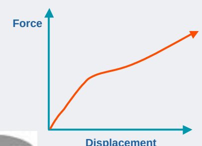
Accurately represents monotonic axial loading

Accurately represents cyclic axial loading



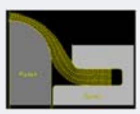
2) Challenge the material model to predict stress/strain behavior in other loading modes





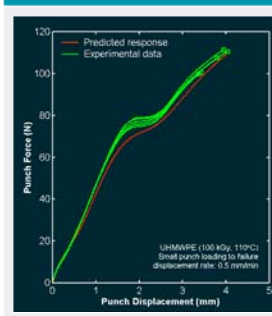
Experiment

Small punch test: equibiaxial loading



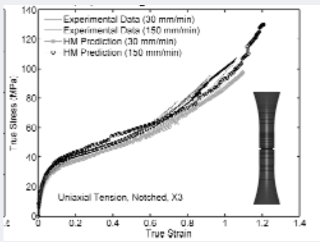
Prediction

The model works for conventional and crosslinked UHMWPE formulations - biaxial



Accurately predicts equibiaxial monotonic loading

The model works for conventional and crosslinked UHMWPE formulations - triaxial



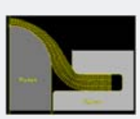
Accurately predicts notched monotonic loading

Summary of Material Parameters: 13 parameters
4 vary with UHMWPE formulation

Material Parameters	
E_e	Elastic modulus of linear spring
υ_e	Poisson's ratio of linear spring
μ_A	Shear modulus of backstress network
λ_A^{lock}	Locking chain stretch of backstress network
κ_A	Bulk modulus of backstress network
S_{bi}, S_{bf}	Initial and final flow resistance of backstress network
α_B	Transition rate of distributed yielding
τ_B^{base}	Initial yield strength of backstress network (B)
τ_P^{base}	Initial yield strength of viscoplastic network P
m_B, m_P	Rate dependence of B and P networks
$\hat{p}$	Pressure dependence of yield stress

Can we also predict failure?
Examine stress or strain-based failure criteria

Experiment



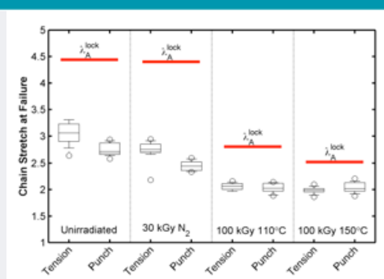
Prediction

Eight failure criteria examined

The chain stretch failure model is significantly better than other failure models for UHMWPE

Bergström, Rimnac, Kurtz
JOR, 2005

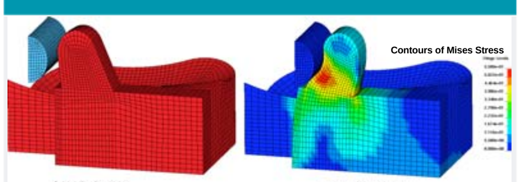
Failure appears to be related to maximum chain stretch capability of UHMWPE



Bergström, Rimnac, Kurtz
JOR, 2005

CASE SCHOOL OF ENGINEERING

Applications



3D simulation of a total knee replacement component

CASE SCHOOL OF ENGINEERING

HM Summary

- The Hybrid Model (HM) accurately predicts the large-strain, time-dependent behavior of UHMWPE
- The HM can be calibrated to uniaxial data and used to accurately simulate multiaxial deformation states
- The HM has been implemented as a user material model for ls971

Future Work

- Continue to follow retrieved THR and TKR components - closes the "design loop"
- Develop a meaningful fatigue test that provides design input
- Incorporate fatigue failure damage rule into the HM constitutive model for UHMWPE
- Prediction of fracture risk with new UHMWPE formulations/new implant designs (pre-clinical screening - the virtual patient) is the goal

Overall Summary

- The orthopaedic research community today has a much better understanding of the physical, chemical, mechanical, and clinical consequences of exposure of UHMWPE to ionizing radiation
- Advances in sterilization include strategies to reduce or inhibit oxidation during and after sterilization with gamma radiation via barrier packaging and processing treatments to extinguish long-lived free radicals
- Approaches to modify UHMWPE for reduction of wear of THR and TKR components continue to evolve (e.g., vitamin E as anti-oxidant so as to maintain crystallinity)
- Prediction of fracture risk with new UHMWPE formulations/new implant designs (pre-clinical screening - the virtual patient) is a goal

Collaborators and Students

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Celebrating more than thirty years of interdisciplinary musculoskeletal research.