An investigation on the surface and bulk mechanical properties of clinically relevant UHMWPE formulations using nanoindentation and compression testing

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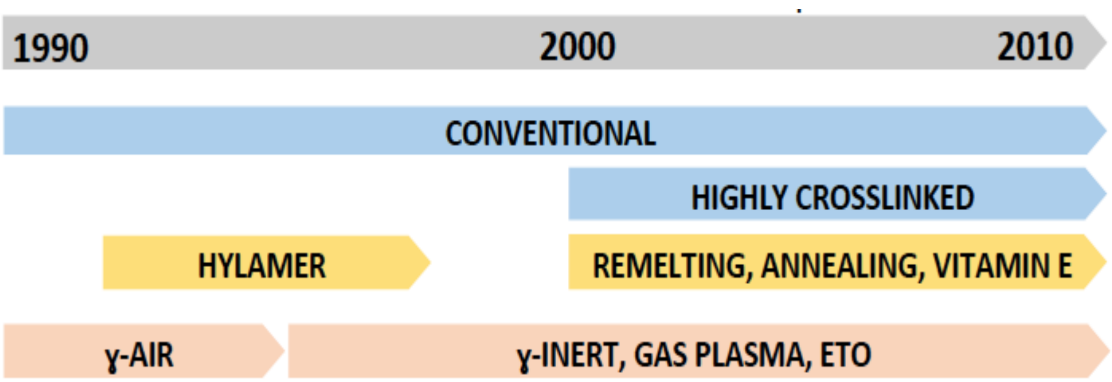
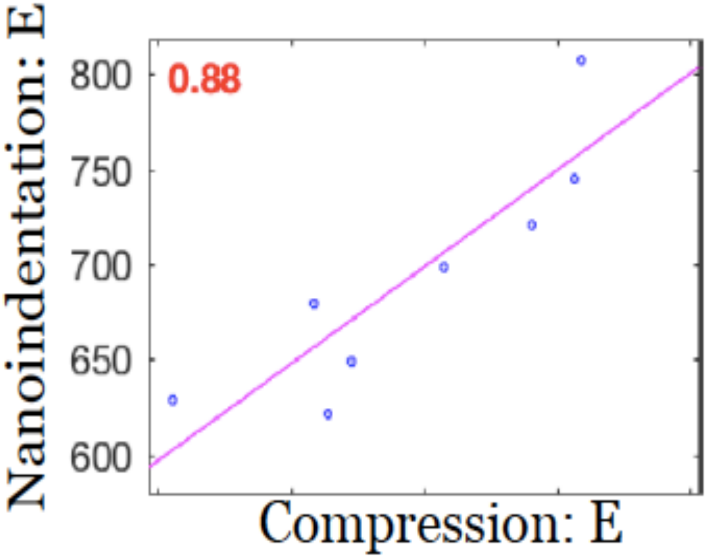
Motivation for Study

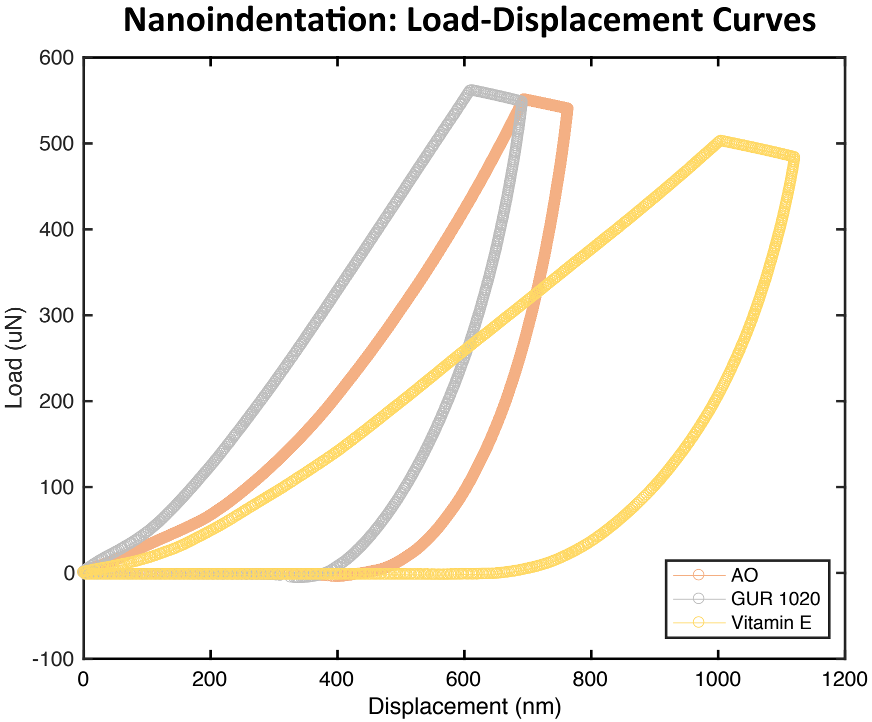
- **900,000 TJR annually in U.S. and majority utilize UHMWPE**
- **Simple mechanical characterization methods are needed for material comparisons and retrieval analysis**
- **Numerous clinical formulations of UHMWPE in varying crosslink dose, thermal treatment and antioxidant chemistry**

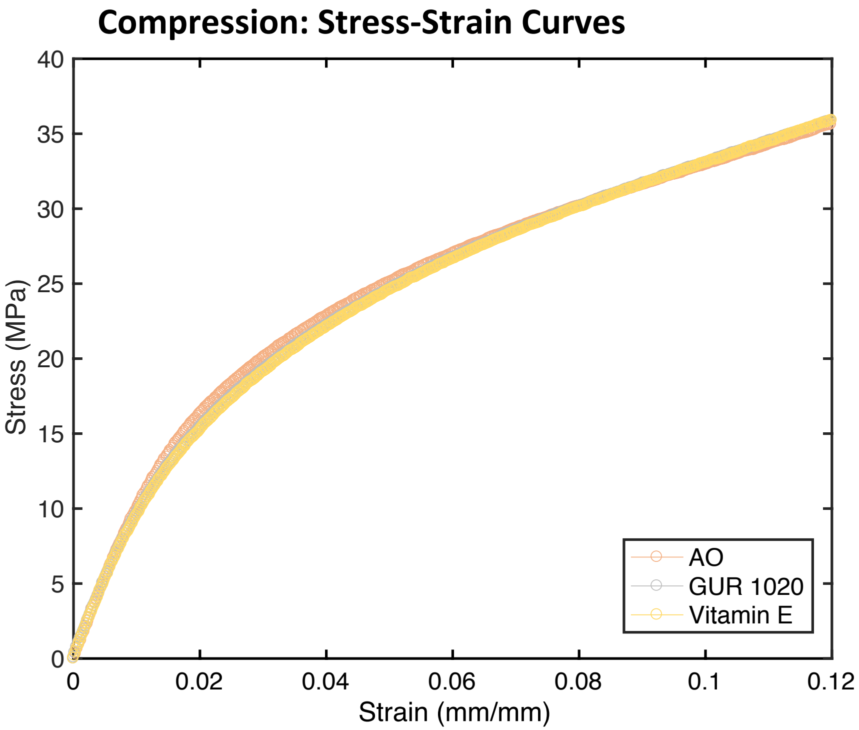


healthbase.com, springerimages.com

Correlation between compression and nanoindentation







Previous work

Polymers

Tribological and nanomechanical properties of unmodified and XL- UHMWPE for TJR.

J. Zhou, A. Chakravartula, L. Pruitt, K. Komvopolous

Energetically Treated Polyethylene Surfaces.

C. Klapperich, L. Pruitt, K. Komvopolous

Nanomechanical properties of polymers.

C. Klapperich, K. Komvopolous, L. Pruitt

Nanomechanical Analysis of Surface Properties and Early Wear Mechanisms in UHMWPE.

A. Chakravartula, Y. Zhou, K. Komvopolous, L. Pruitt

UHMWPE-Retrievals

On the assessment of oxidative and microstructural changes after in vivo degradation of historical UHMWPE knee components by means of vibrational spectroscopies and nanoindentation.

FJ Medel, C. Rimnac, SM Kurtz

Micromechanics of shelf-aged and retrieved UHMWPE tibial inserts: indentation testing, oxidative profiling, and thickness effects.

James D. Wernele, Jeremy L. Gilbert

Biological

Finger Joints

C. Li, D. Ebenstein, K. King, L. Pruitt

Articular cartilage

C. Li, K. King, L. Pruitt

Hydrated Materials for Application to Vascular Tissues.

D. Ebenstein, L. Pruitt

Porcine costal cartilage

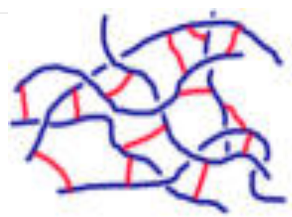
S. Gupta, J. Lin, P. Ashby, L. Pruitt

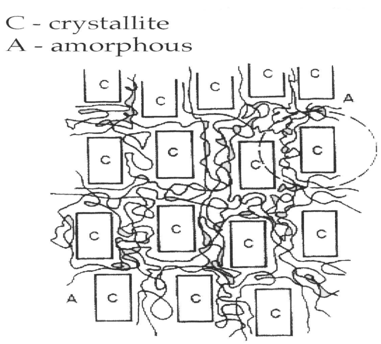
Nanomechanical Properties of Calcification, Fibrous Tissue, and Hematoma from Atherosclerotic Plaques.

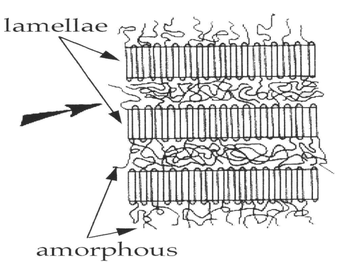
D. Ebenstein, D. Coughlin, J. Chapman, C. Li, L. Pruitt

UHMWPE Material Type and Manufacturer

GUR 1020 (Orthoplastics)	GUR 1020 AO (Depuy)	GUR 1020 VE (Orthoplastics)	GUR 1050 (Orthoplastics)
GUR 1020 35kGy (Orthoplastics)	GUR 1020 AO 80kGy (Depuy)	GUR 1020 VE 50 kGy (Orthoplastics)	GUR 1050 75kGy RM (Quadrant)
GUR 1020 75kGy RM (Orthoplastics)		GUR 1020 VE 75kGy (Orthoplastics)	
		GUR 1020 VE 100 kGy (Orthoplastics)	
		GUR 1020 VE 125kGy (Orthoplastics)	



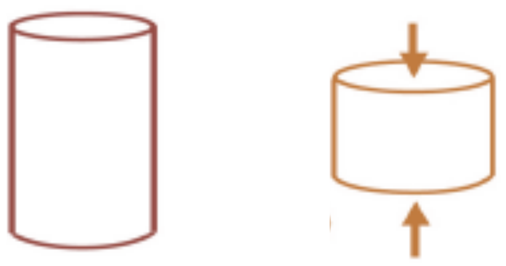


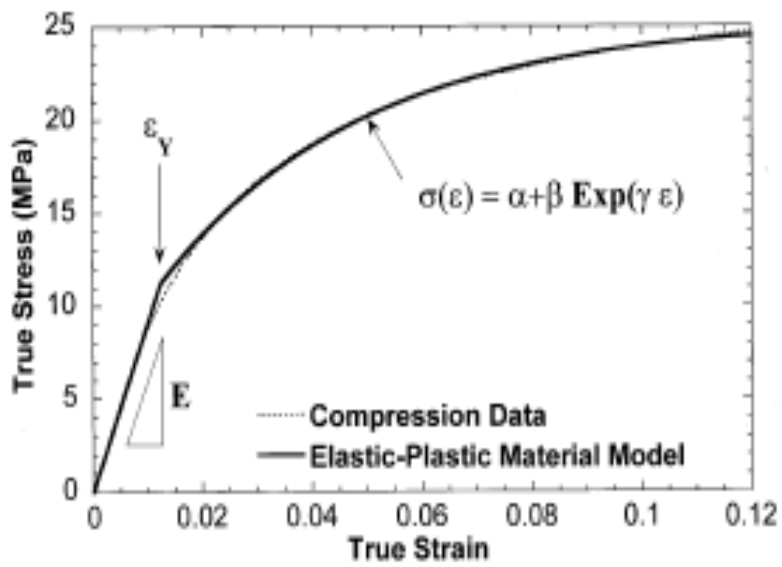


2 resins (1020/1050)
Range of crosslinking (Doses: 35-125 kGy)
2 antioxidants: AO and VE

Methods: Compression and nanoindentation

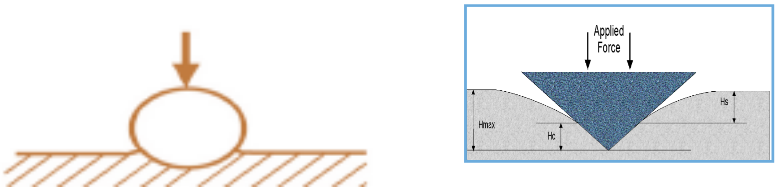
Compression testing

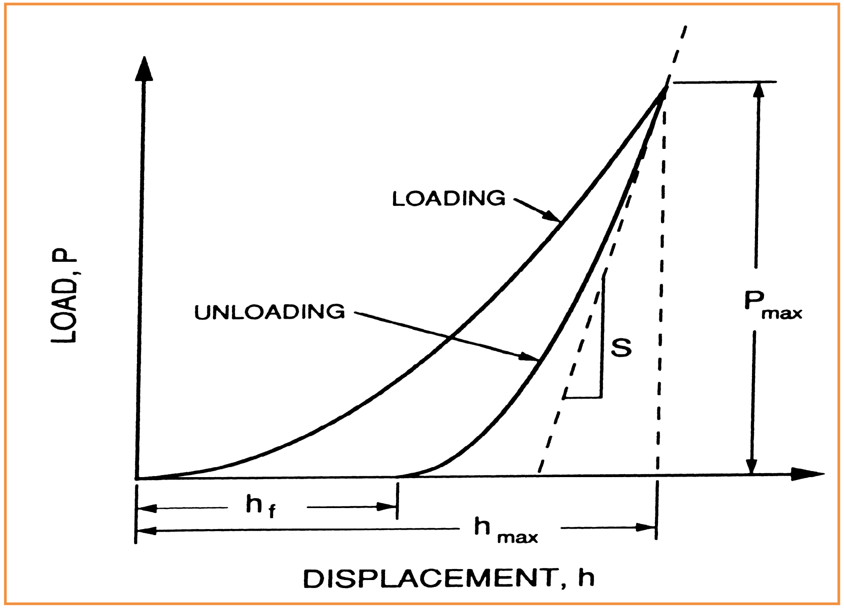




S.M Kurtz et al./Biomaterials 19 (1998) 1989-2003

Nanoindentation testing

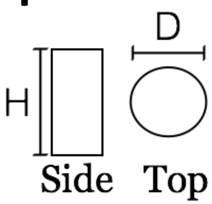




M.F. Doerner and W.D. Nix. J Mater Res, 1:601 (1986).
Oliver WC and Pharr GM. J. Mat. Res. 7:156 (1992)

Compression Stress-Strain Acquisition

Specimen Dimension



H: 15 mm
D: 10 mm

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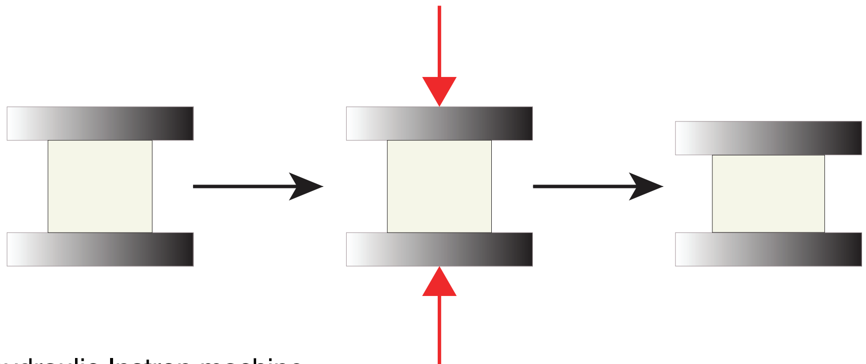
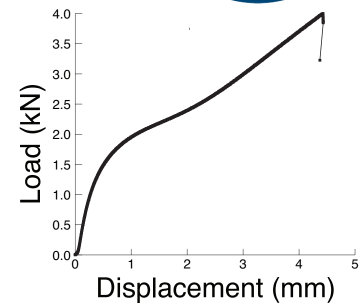
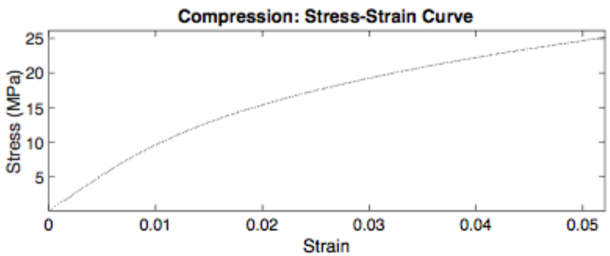


hydraulic Instron machine

Displacement rate: 18mm/min
Strain rate: 0.02/s





Calculate stress and strain

Is there a toe-region in the data?

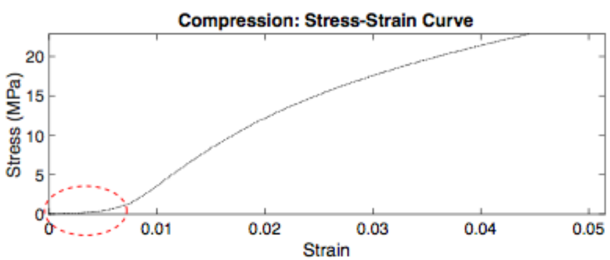
No

Yes

Remove toe-region and re-zero stress and strain

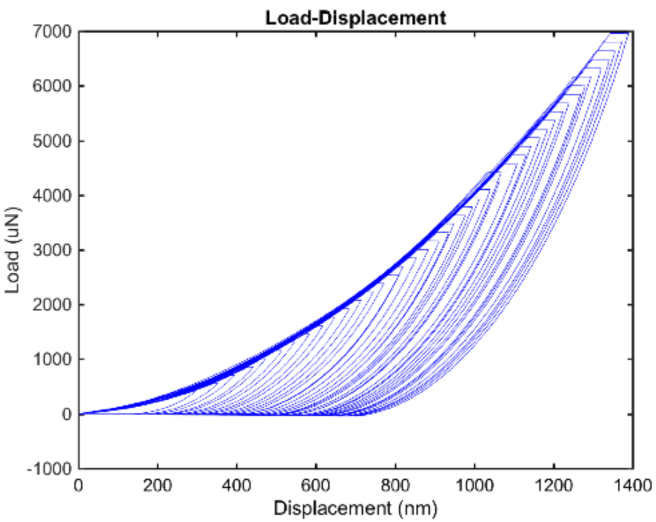
Elastic Modulus
Find the slope of the initial linear region of stress-strain curve

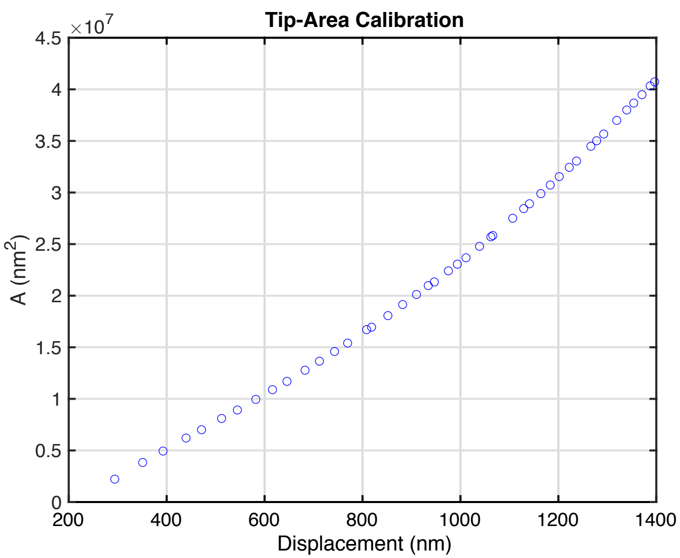
Yield Strength:
Use of 0.2% offset method



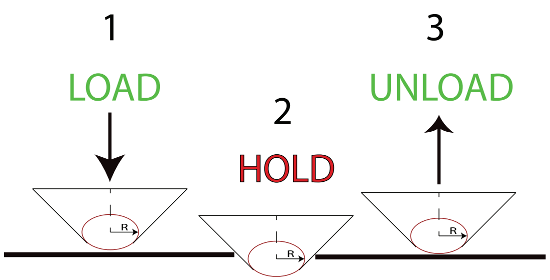
Nanoindentation: Load-Displacement Acquisition

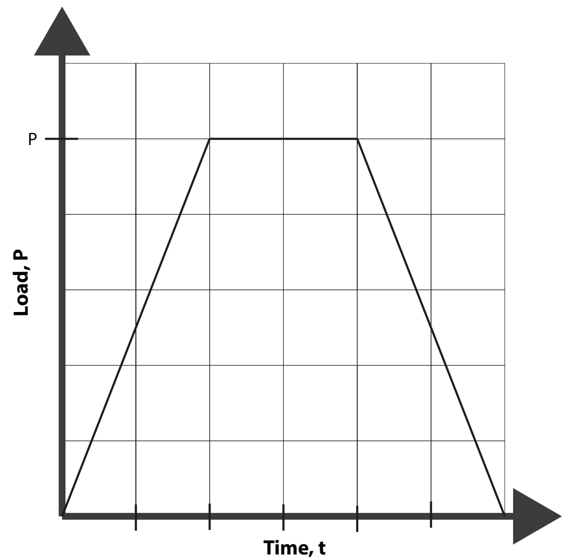
$$A_c(h_c) = C_o h_c^2 + C_1 h_c^1 + C_2 h_c^{1/2} + C_3 h_c^{1/4} \quad \textbf{(1)}$$

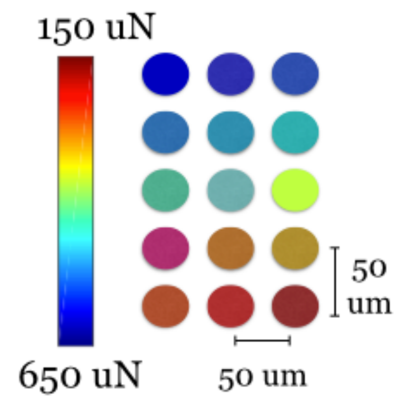




Load-Function Profile







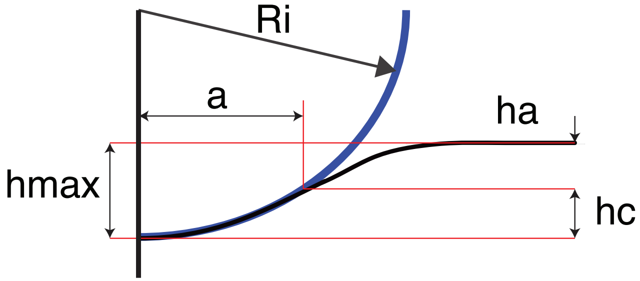
X 3 per sample

- Sample size per material group = 5

Tip-radius: 20 um
Load-Rate: 30 uN/s
Hold: 10 seconds

Overview: Nanoindentation Theory

Relation between load and penetration



$$P = \frac{4\mu a}{1-\upsilon} h$$

I.N. Sneddon, Int. J. Engng. Sci. 3, 47 (1965) .

Stiffness to Reduced-Modulus

$$S = \frac{dP}{dh}$$

$$S = \frac{dP}{dh} = \frac{2\sqrt{A_c}}{\sqrt{\pi}} E_r$$

$$E_r = \frac{1}{2} \frac{\sqrt{\pi}}{\sqrt{A_c}} \frac{dP}{dh}$$

Hardness

$$H = \frac{P_m}{A_c}$$

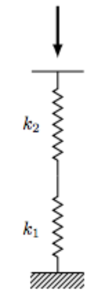
Contact area

$$A_c(h_c) = C_0 h_c^2 + C_1 h_c^1 + C_2 h_c^{1/2} + C_3 h_c^{1/4}$$

Reduced-Modulus (combined modulus) to Elastic Modulus

$$\frac{1}{E_r} = \frac{1-\upsilon_i^2}{E_i} + \frac{1-\upsilon_s^2}{E_s}$$

Er: Reduced Modulus **Es:** Sample modulus **Ei:** Indenter modulus



Poisson's ratio = 0.46 for UHMWPE [1]

[1] S.M. Kurtz (2009). *UHMWPE Biomaterials Handbook*.

Determination of reduced elastic modulus and hardness

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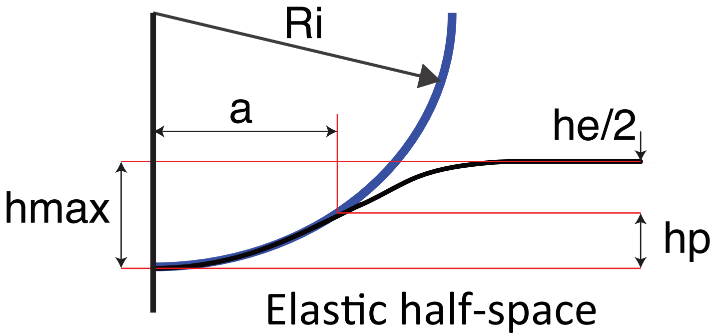

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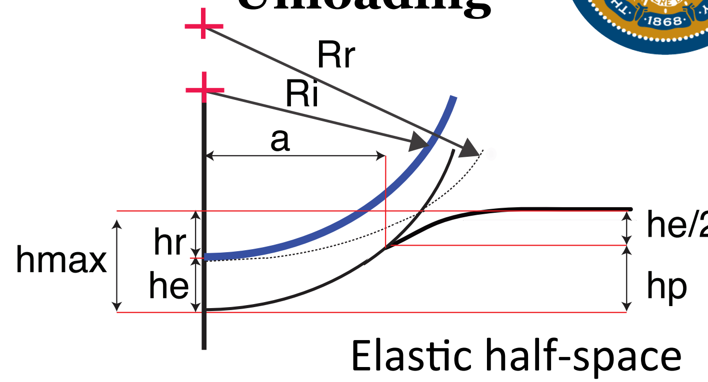
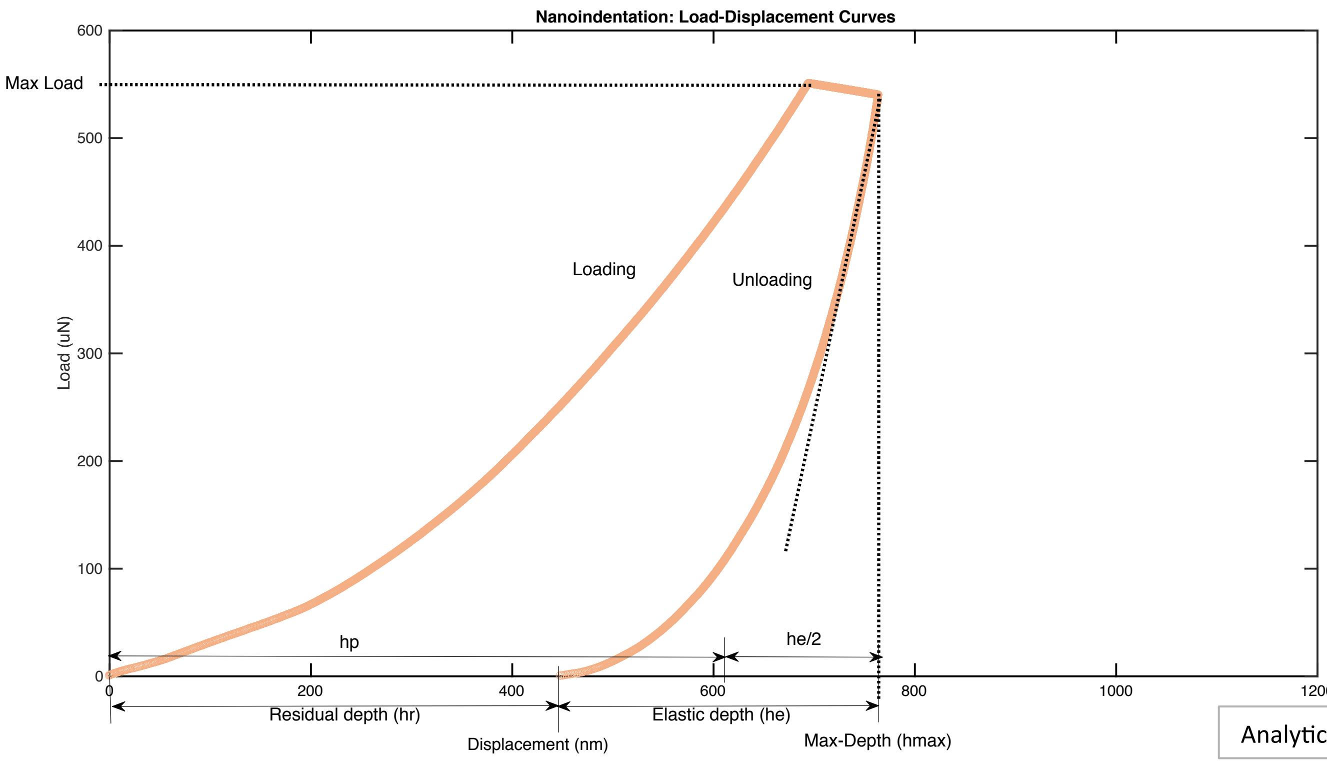
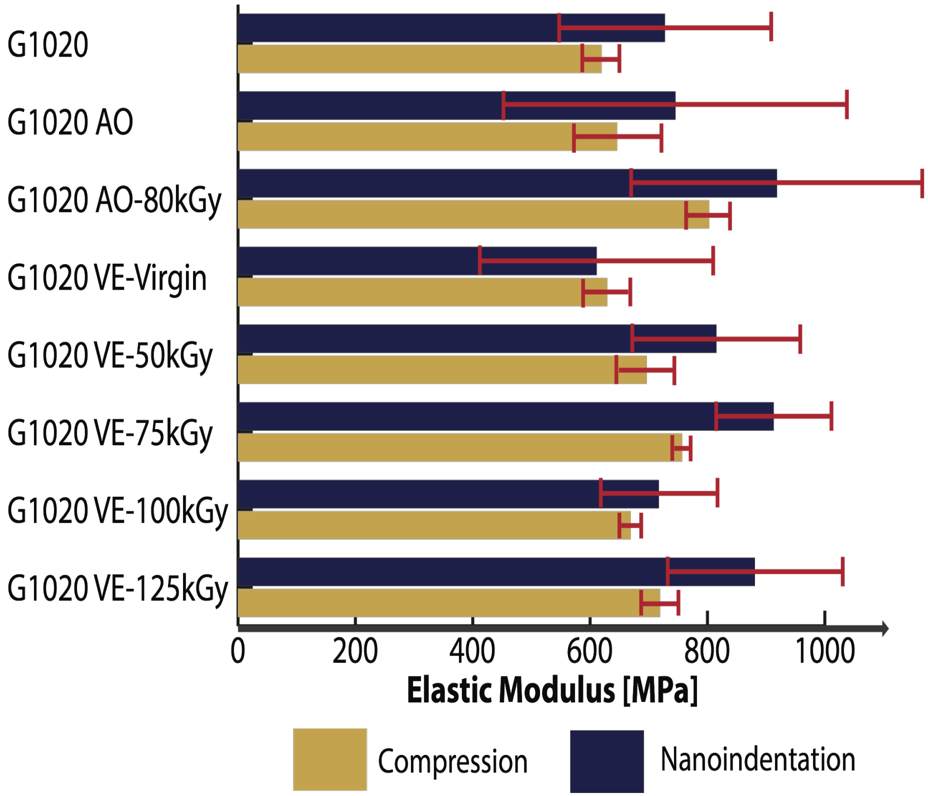


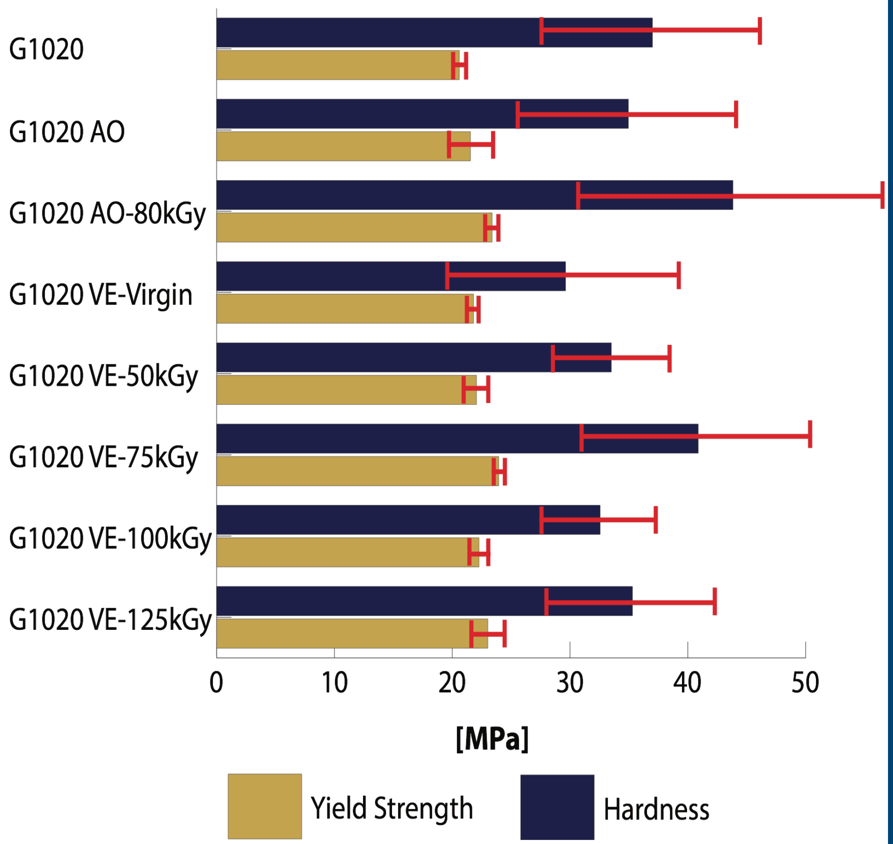


Pm: max load.
hr: residual depth.
he: elastic depth.
hmax: depth of penetration.
hp: depth of the circle of contact from the specimen free surface.
he/2: distance from the bottom of the contact to the contact circle.
a: radius of circle in contact.

Analytical model based on the Doerner –Nix Model

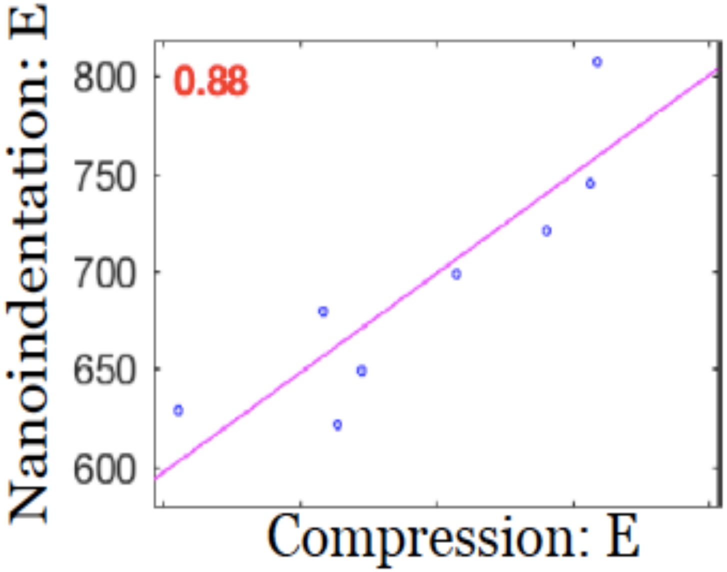
Results: Nanoindentation and compression mechanical properties





Conclusions

- Our study shows a strong correlation between modulus measurements made though nanoindentation and compression.
- Nanoindentation provides a tool for the surface characterization of UHMWPE. The method provides a valid technique to determine modulus and hardness across climical formulations of UHMWPE.



Ongoing work

Utilization of nanoindentation for the characterization of reduced modulus and hardness in retrievals.

Correlation between surface properties and microstructure.

Acknowledgments

- We would like to thank Orthoplastics, Quadrant and DePuy for supplying materials
- Funding has been provided by National Science Foundation (NSF graduate fellowship) and endowment from Lawrence Talbot Professorship.