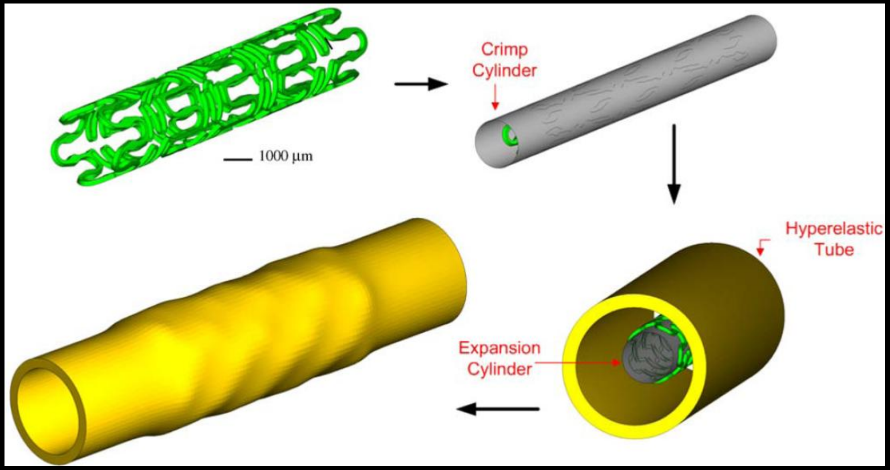
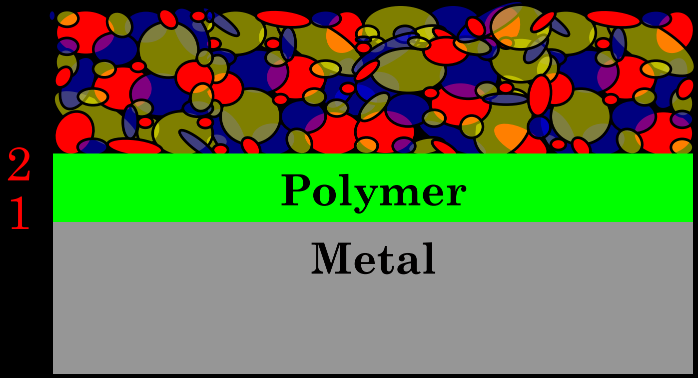
Adhsion and Interfacial Failure in Drug Eluting Stents

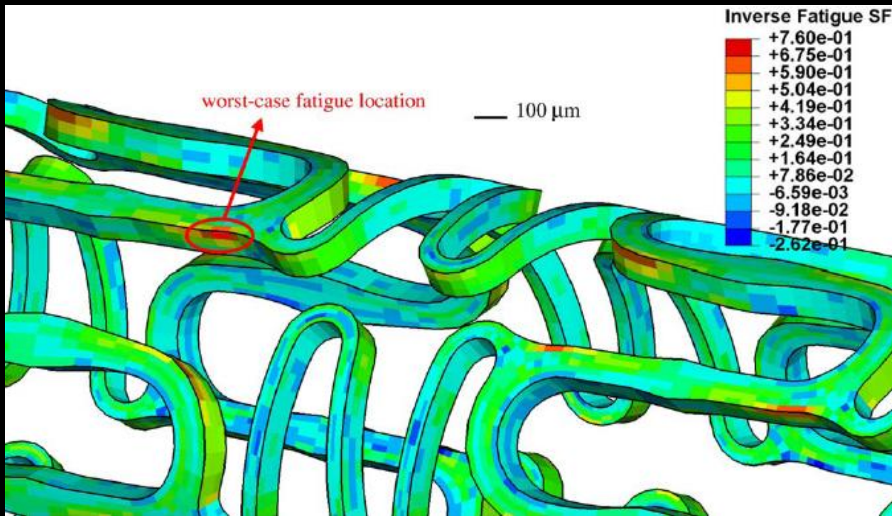
Background and Introduction

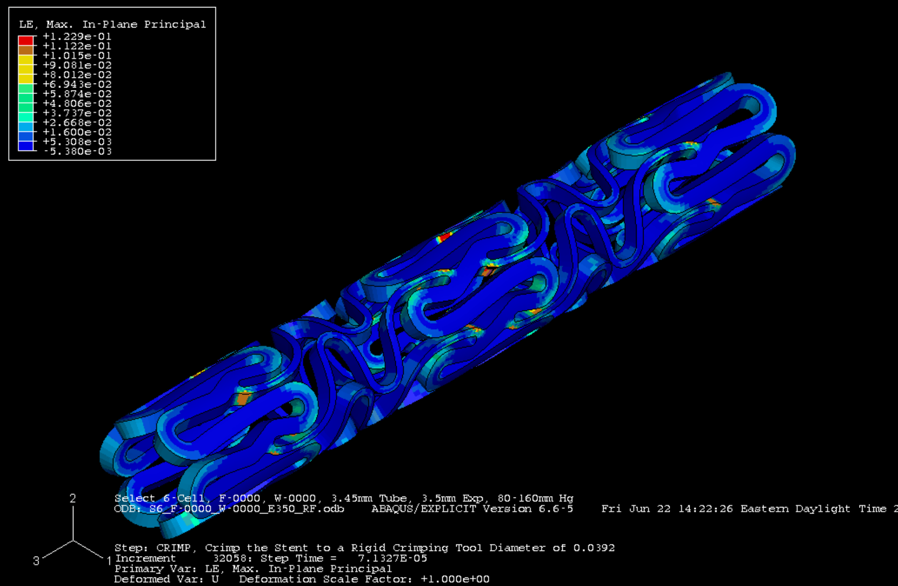
- *Cardiovascular disease is the leading cause of death across the world*
- *It represents about 30% of all deaths*
- *Stents represent a life saving technology for arterioschlorosis*
- *Drug Eluting Stents (DES) reduce the possibility of clotting after stent insertion*

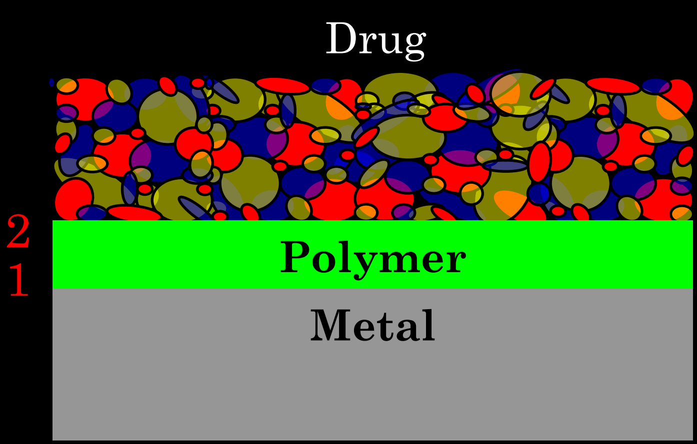


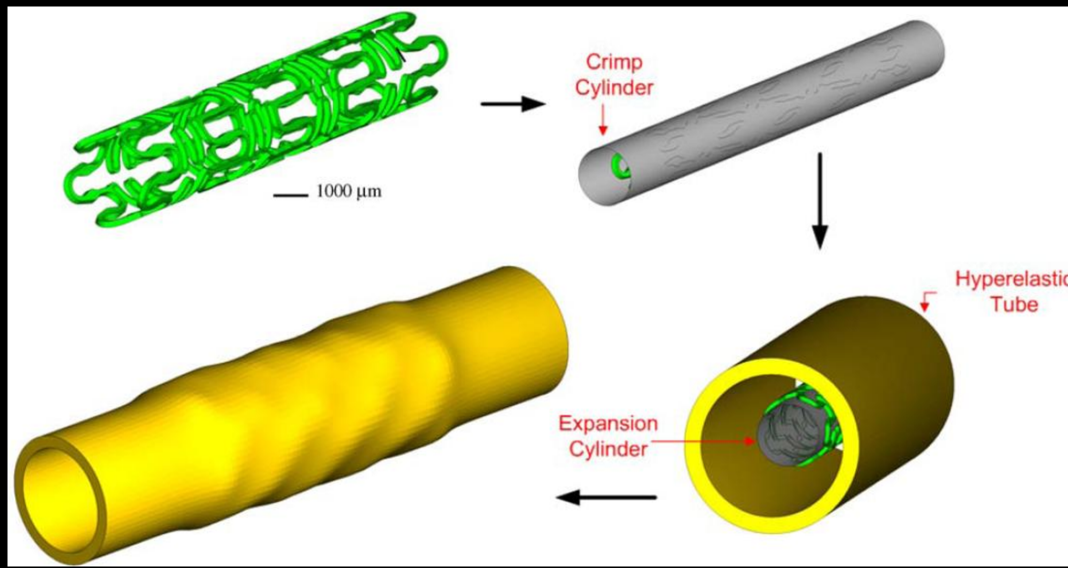


Drug-Eluting Stents



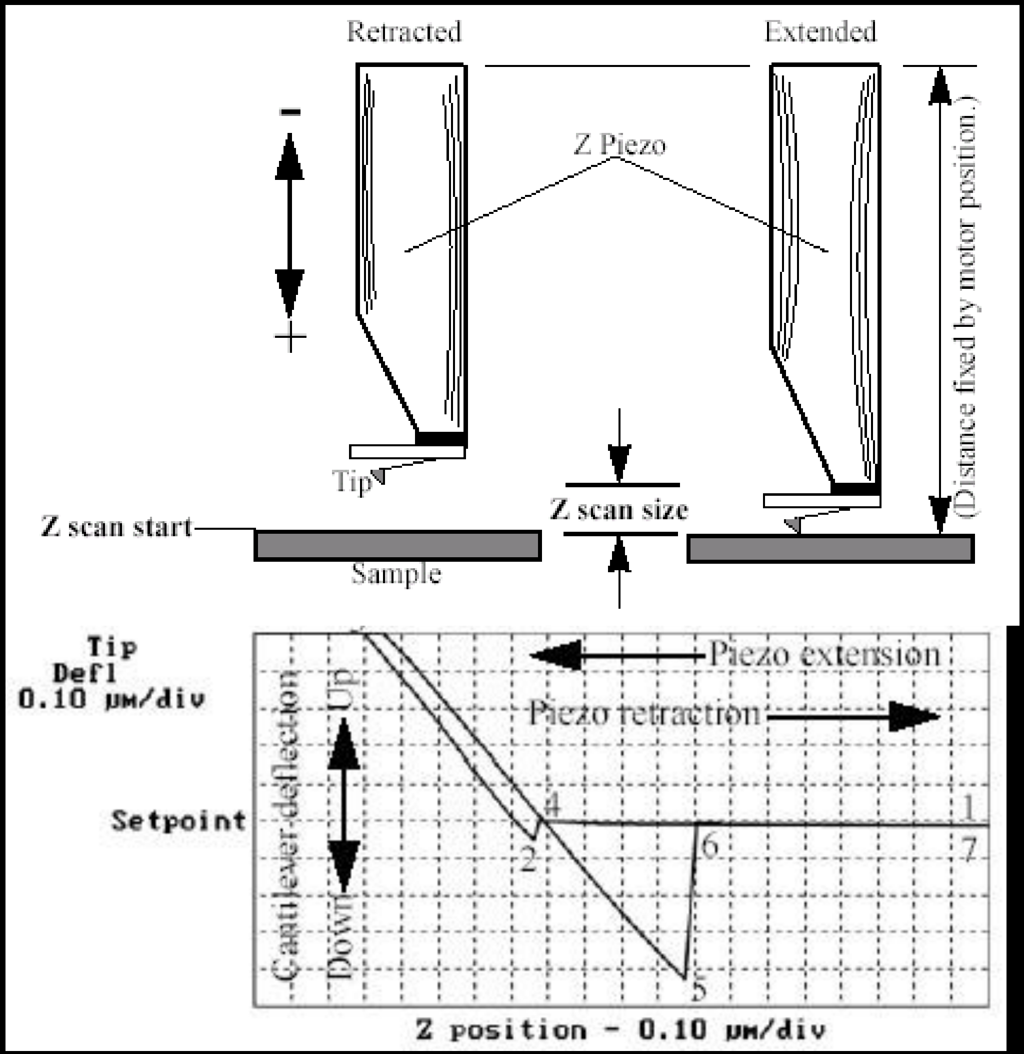


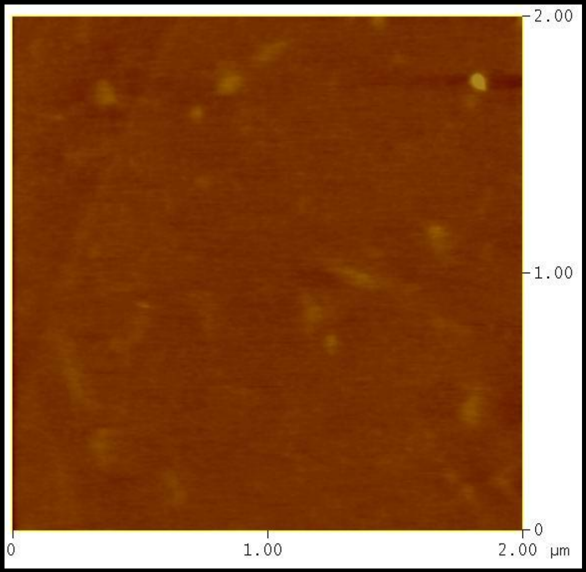




Marrey RV et al. (2006)
Biomaterials 27:1988–2000

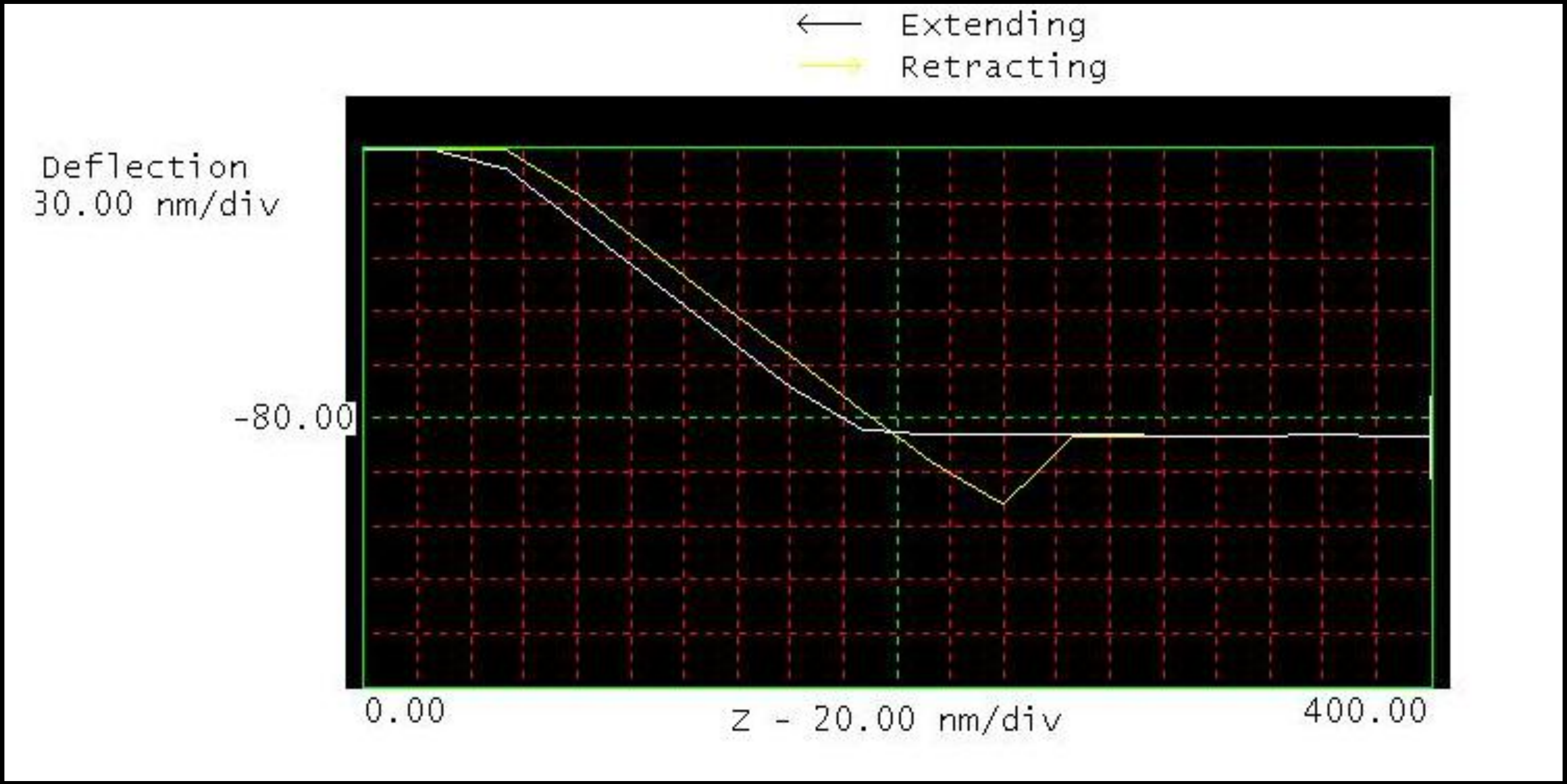
AFM Adhesion Pull-Off Force Measurement



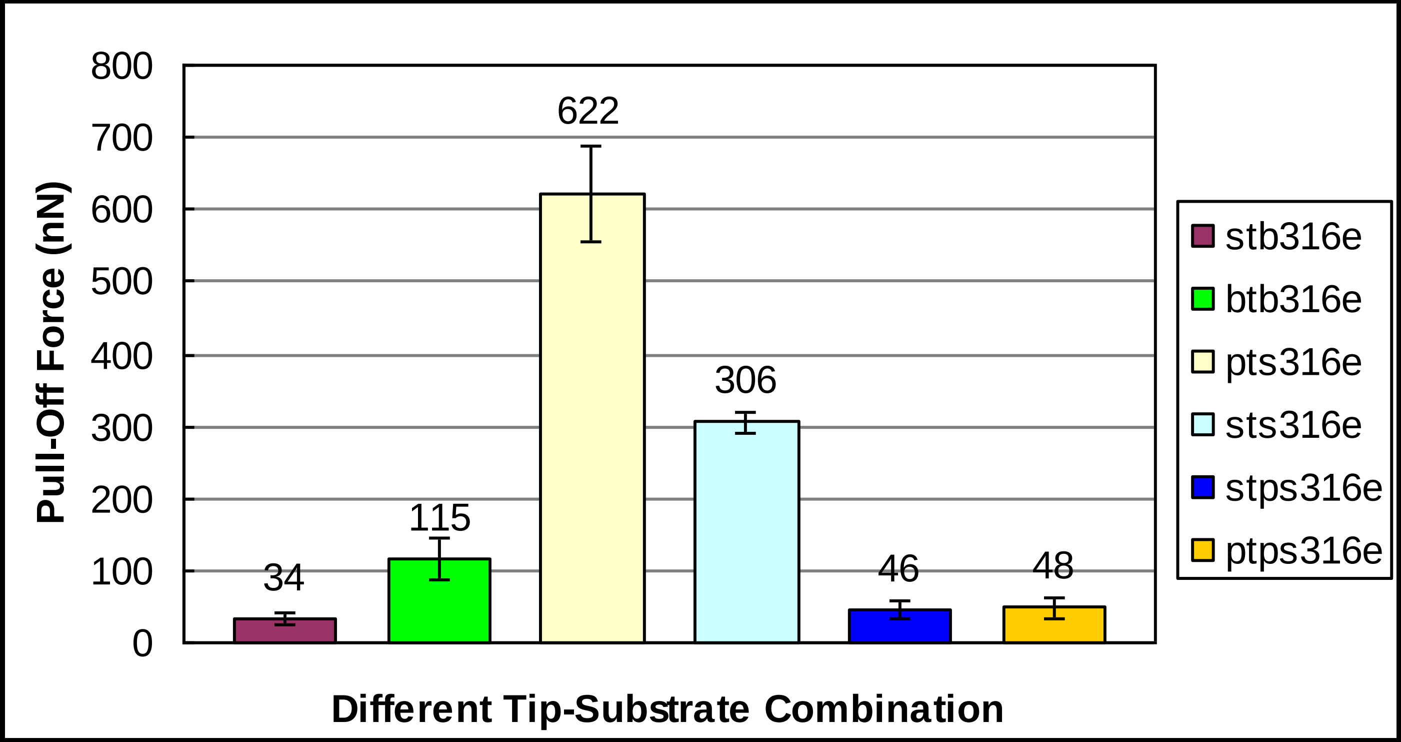


Princeton University

AFM Adhesion Pull-Off Force Measurement

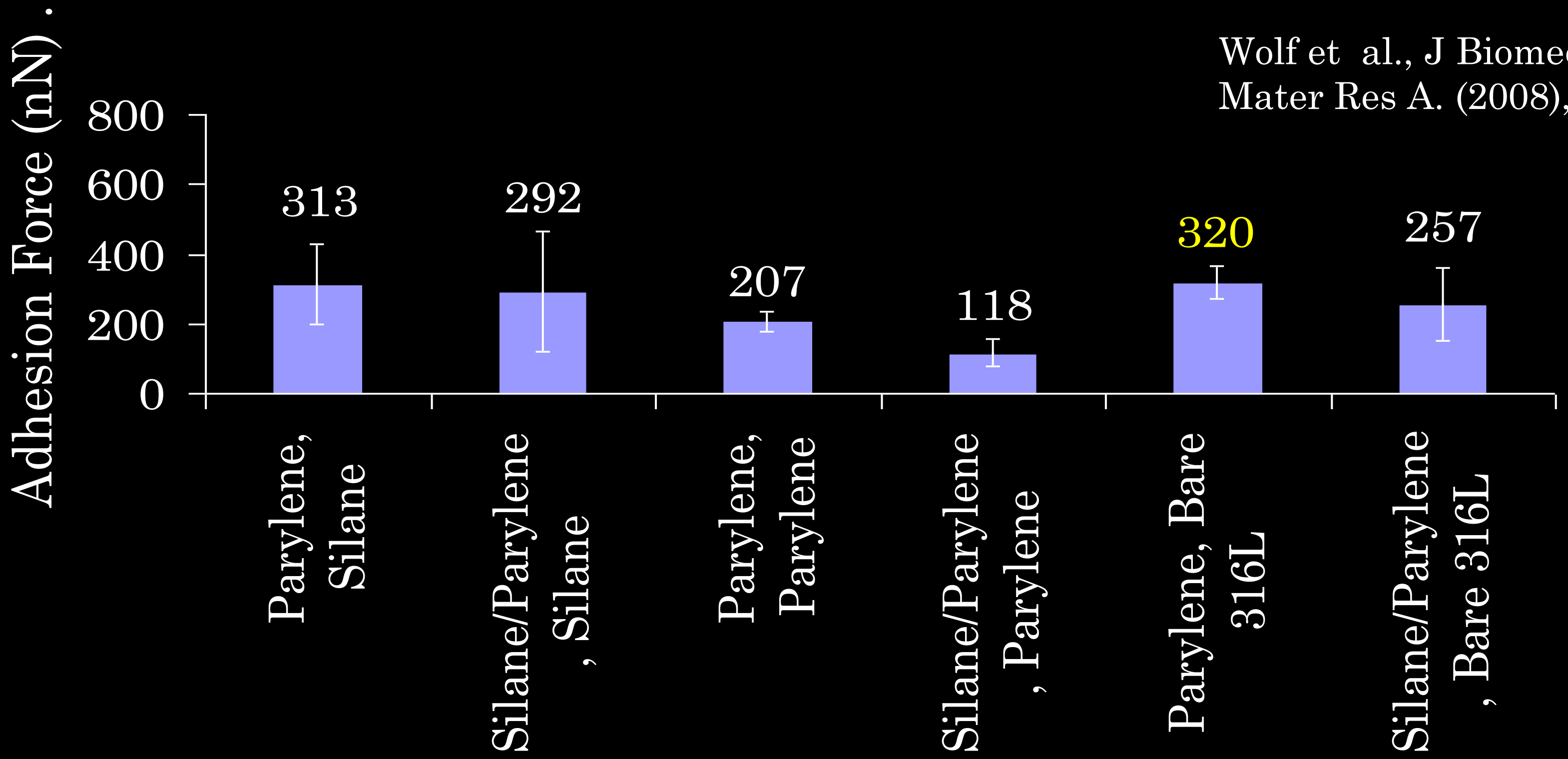


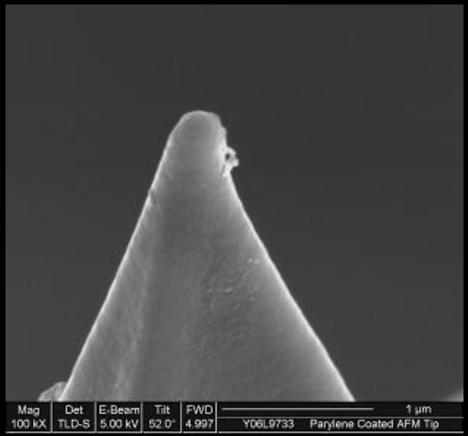
AFM Adhesion Pull-Off Force Measurement



Experiments: AFM

Wolf et al., J Biomed Mater Res A. (2008), Feb.

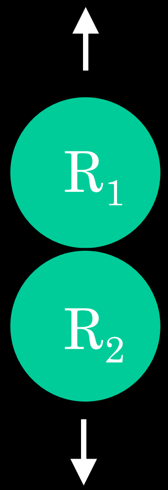




Surface Coating	Average Coupon rms Roughness (nm)	Coupon STD (nm)
EP 316L	106	42

Coating	Average Radius (nm)	Radius STD (nm)
Parylene C	370	31

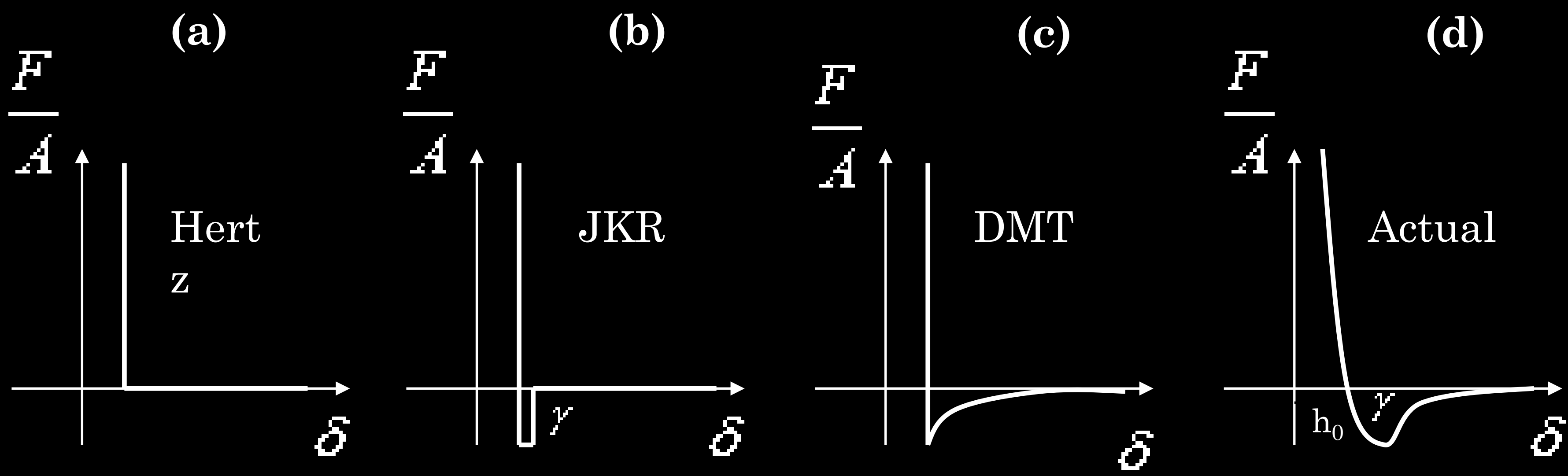
Adhesion Theory



$$F_{ad} = \bar{F}\pi\gamma R$$

$$\frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2}$$

$$\gamma = \gamma_1 + \gamma_2 - \gamma_{12}$$



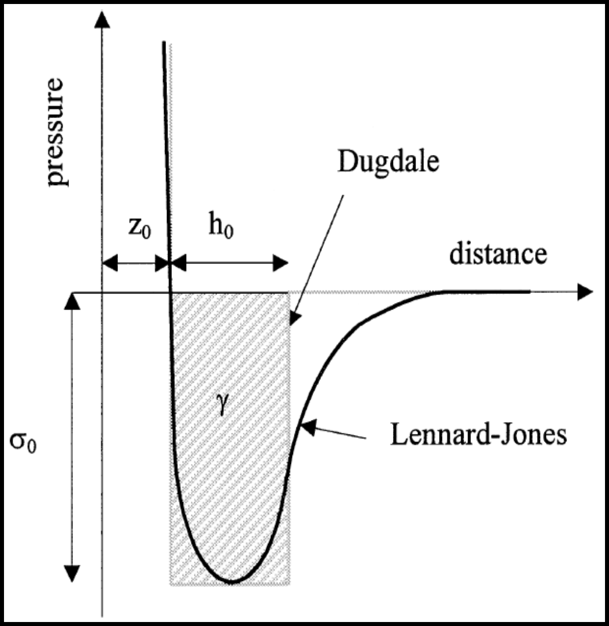
Johnson KL, Kendall K, Roberts AD (1971) *Proc. R. Soc. London, Ser.A*, 324,

Derjaguin BV, Muller VM, Toporov YP (1975) *J. Colloid Interface Sci.*, 53, 314.

Adhesion Theory

Johnson–Kendall–Roberts (JKR) model: describes well the contact area when the surface forces are short range in comparison to the elastic deformations they produce (i.e., compliant materials, strong adhesion forces, large tip radii)

$$F_{JKR} = \frac{3}{2}\pi\gamma R$$



Derjaguin–Muller–Toporov (DMT):

applies well in the case of long-range surface forces with an hertzian geometry (i.e., stiff materials, weak adhesion forces, small tip radii)

$$F_{DMT} = 2\pi\gamma R$$

$$\lambda = 2\sigma_0\left(\frac{R}{\pi K^2\gamma}\right)^{1/3}$$

$$\lambda = f(\alpha) = -0.913\ln(1-1.018\alpha)$$

General case

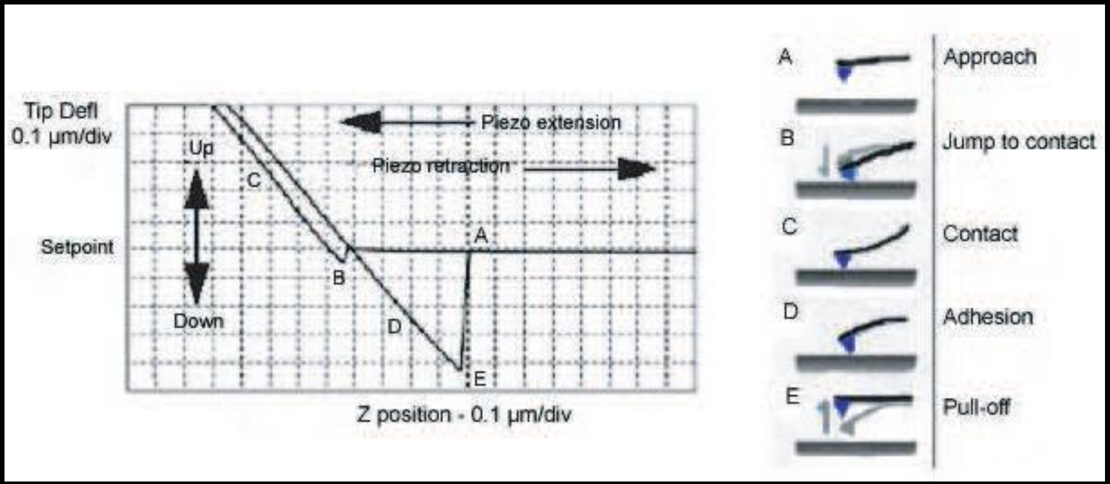
$$F_{ad} = \bar{F}\pi\gamma R$$

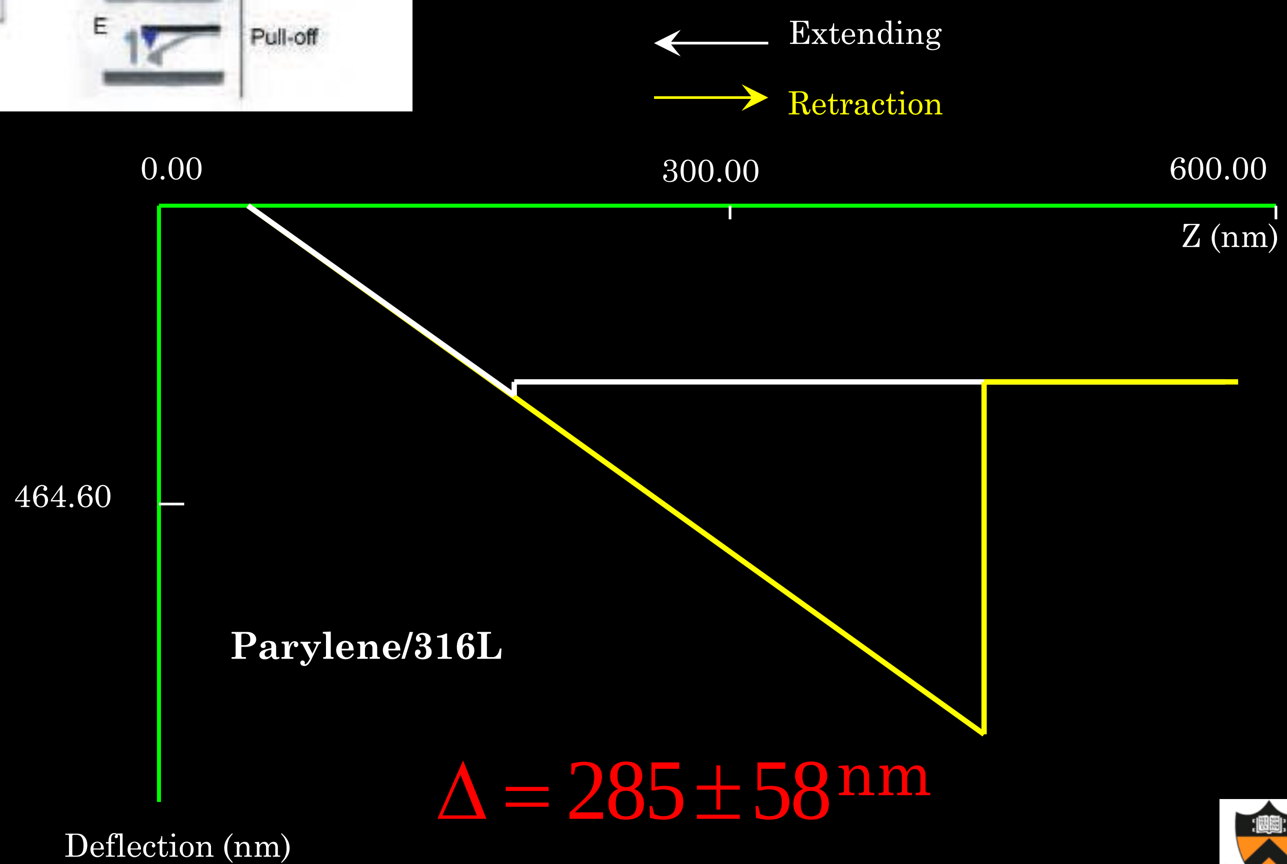
$$\bar{F} = 0.267\alpha^2 - 0.767\alpha + 2.000$$

$$\gamma = \sigma_0 h_0$$

Carpick RW, Ogletree DF, and Salmeron M (1999) *J. Colloid Interface Sci.*, 211, 395.

Typical Force-Displacement Curve





$\Delta = 285 \pm 58^{nm}$

Modeling AFM Adhesion

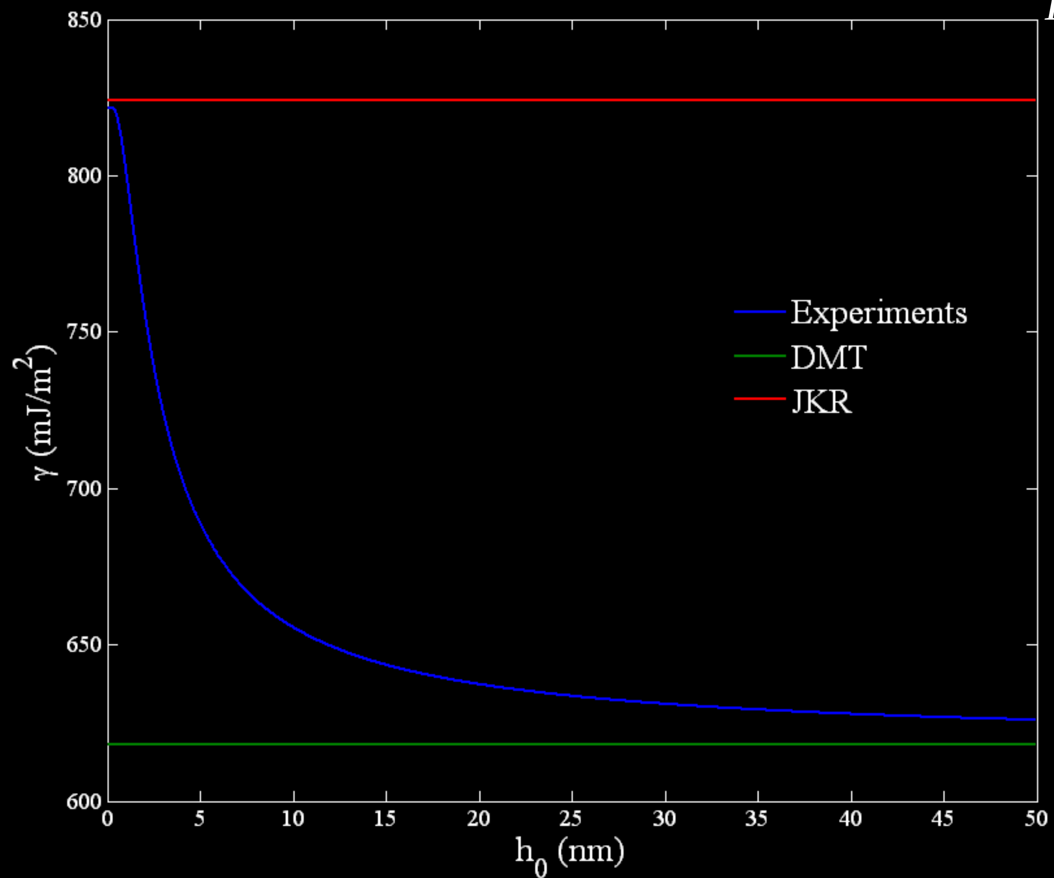
- *Parylene/316L Adhesion Energy:*

$$\lambda = 2\sigma_0\left(\frac{R}{\pi K^2\gamma}\right)^{1/3}$$

$$\lambda = f(\alpha) = -0.913\ln(1-1.018\alpha)$$

$$\overline{F} = 0.267\alpha^2 - 0.767\alpha + 2.000$$

$$\gamma = \sigma_0 h_0$$

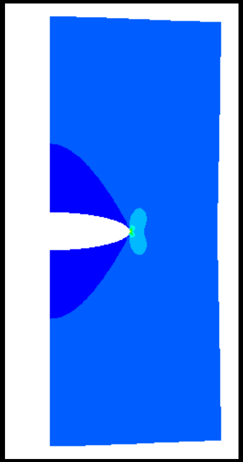


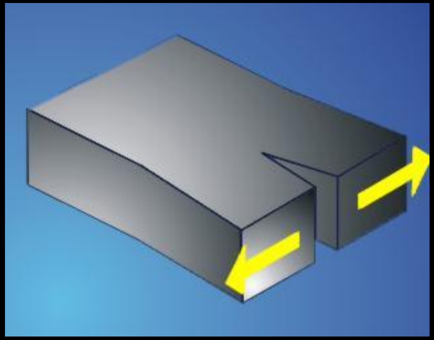
$R = 370\ nm$

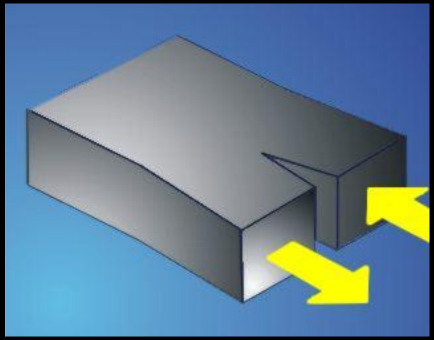
$F_{ad} = 320\ nN$

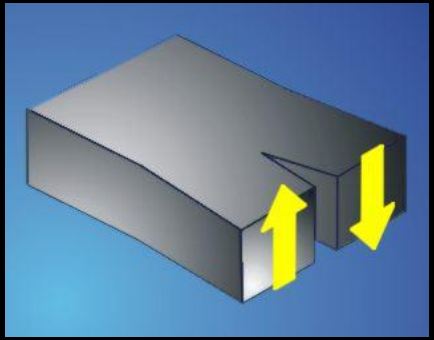
Lorentz–Berthelot mixing rule: $h_{012} = \frac{1}{2}(h_{01} + h_{02})$

Fracture Mechanics







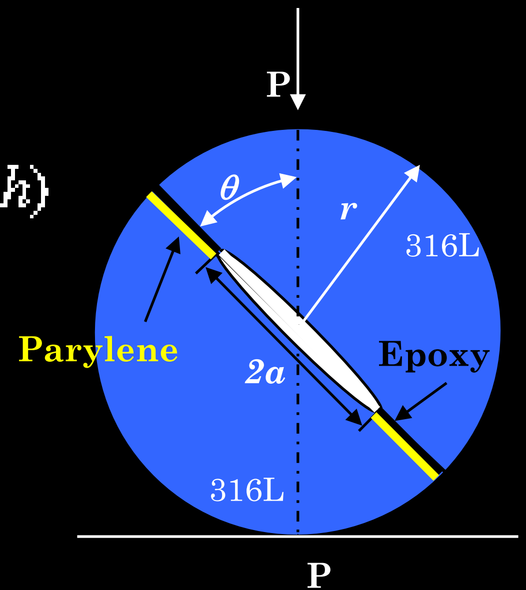


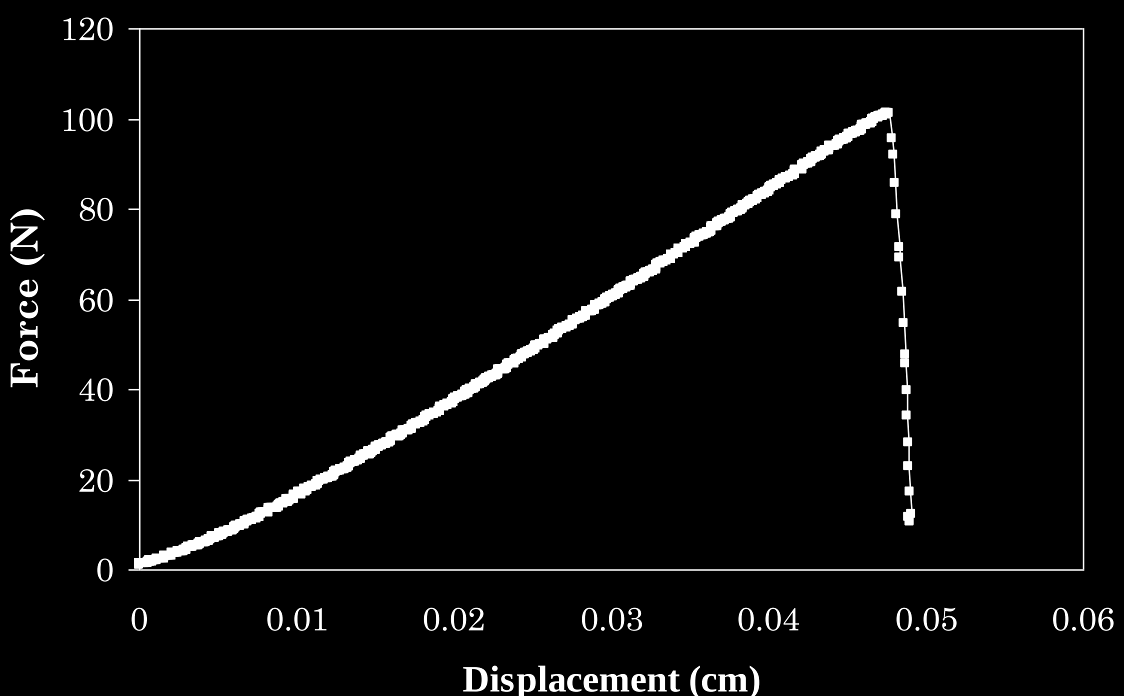
Experiments: Brazil nuts

Energy release rate: $$G = \frac{1}{\overline{E}}\left(K_I^2 + K_{II}^2\right)$$

Loading phase: $$\psi = \tan^{-1}\left(K_{II}/K_I\right) + \omega + \varepsilon \ln\left(\hat{L}/h\right)$$

$$K_I = f_I P a^{-1.2} \qquad K_{II} = f_{II} P a^{-1.2}$$





Wang and Suo, *Acta Metall. Mater*, 38 (7): 1279-1290;

Atkinson et al., *Int J Fract Mech* 18 (4): 279-291.

Typical Fracture Surfaces: Parylene/Steel Sample #8

Figure 9 - Flat Not Marked

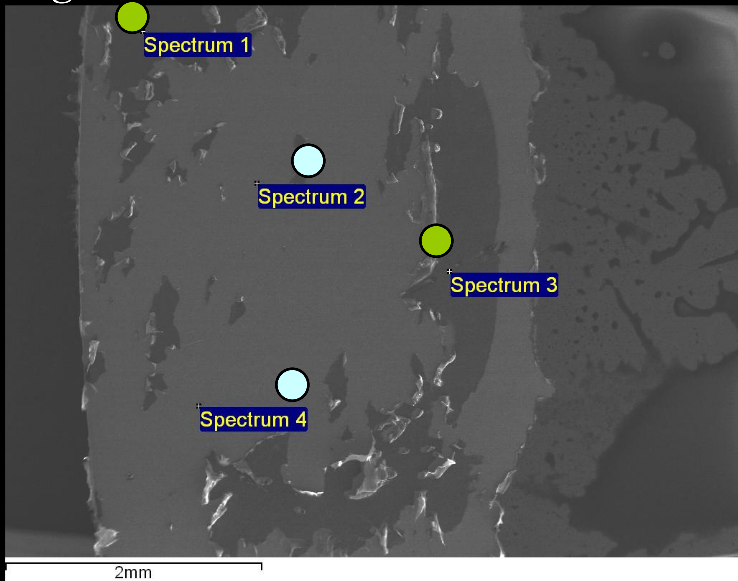


Figure 10 - Notch Not Marked

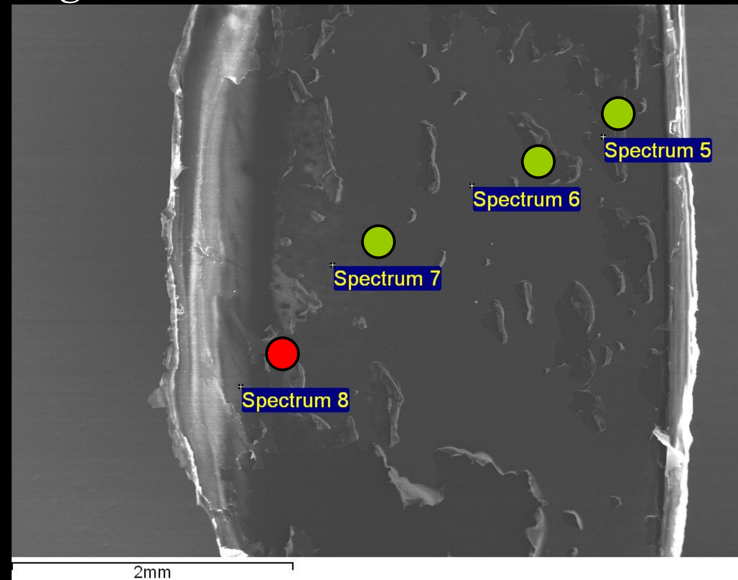


Figure11 – Notch Marked

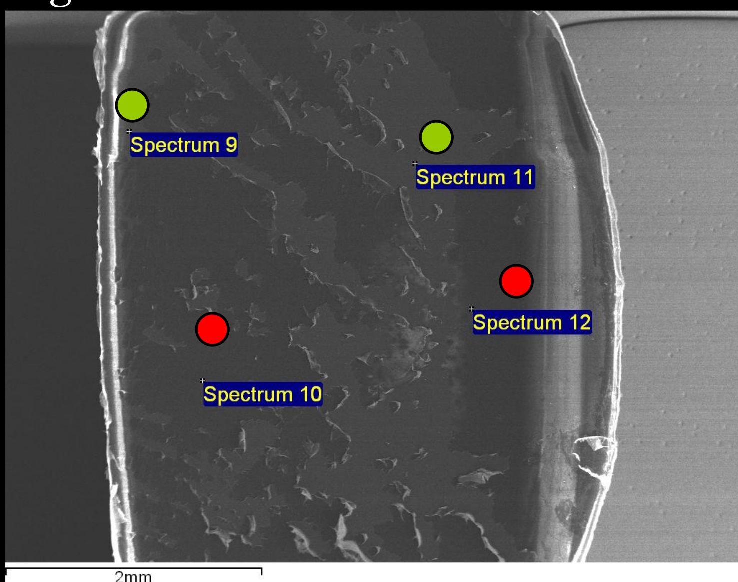
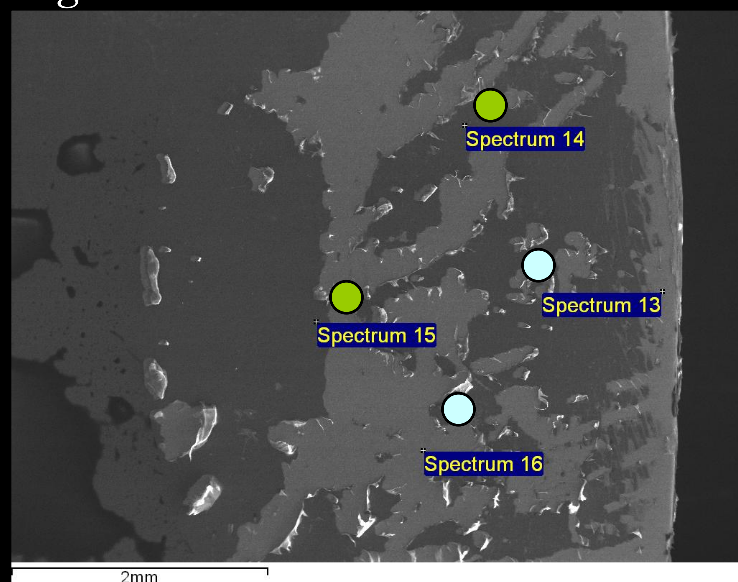


Figure12 – Flat Marked



Parylene: Spectra found >1% Cl

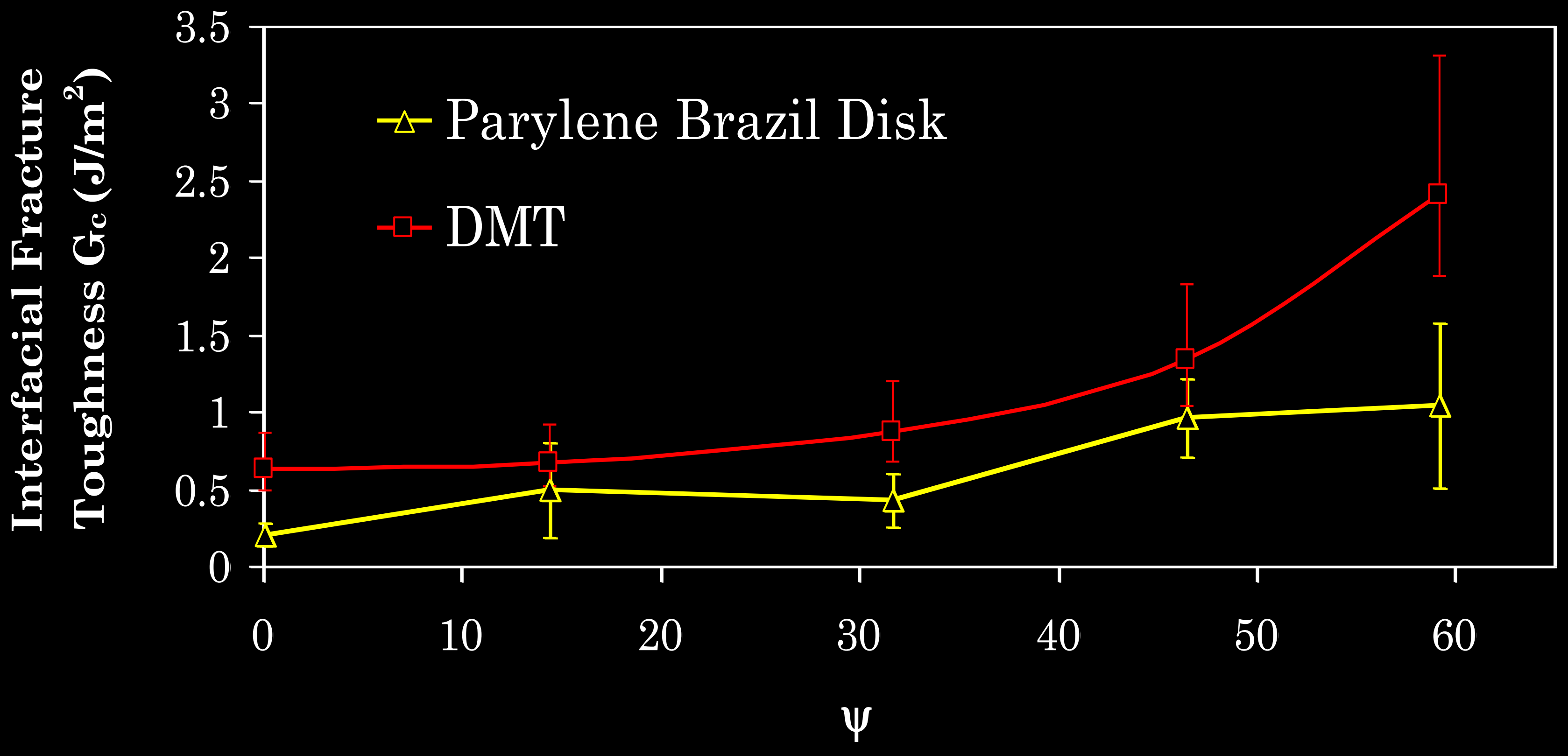
Glue: Spectra found Mainly C and O (Indicative of GLUE)

Steel: Spectra found > 27% Fe (Indicative of steel)

Comparison of DMT models and Interfacial Fracture Experiments

$$F_{DMT} = 2\pi\gamma R$$

$$G = G_0(1 + \tan\Psi^2)$$



Atkinson Model

- *Atkinson et al. (1982)*

$$N_I = (K_I)/\sigma_0\sqrt{\pi a},\ \ N_{II} = (K_{II})/\sigma_0\sqrt{\pi a}$$

$$\sigma_0 = P/\pi l.$$

$$N_I = \sum_{i=1}^{n} T_i(\frac{a}{l})^{2i-2}A_i(\theta),\ \ N_{II} = 2\sin 2\theta \sum_{i=1}^{n} S_i(\frac{a}{l})^{2i-2}B_i(\theta)$$

A_i and B_i are coefficients related to θ

$$\hat{\psi} = tan^{-1}\frac{K_{II}}{K_I} + \omega + \epsilon ln(\frac{\hat{L}}{h})$$

$$G = G_I + G_{II} = \frac{{K_I}^2 + {K_{II}}^2}{E_1} = ({N_I}^2 + {N_{II}}^2)\frac{P^2}{E_1 a}$$

Fundamental Mechanism of Interfacial Fracture

- *Evans and Hutchinson (1982) presented the row model*

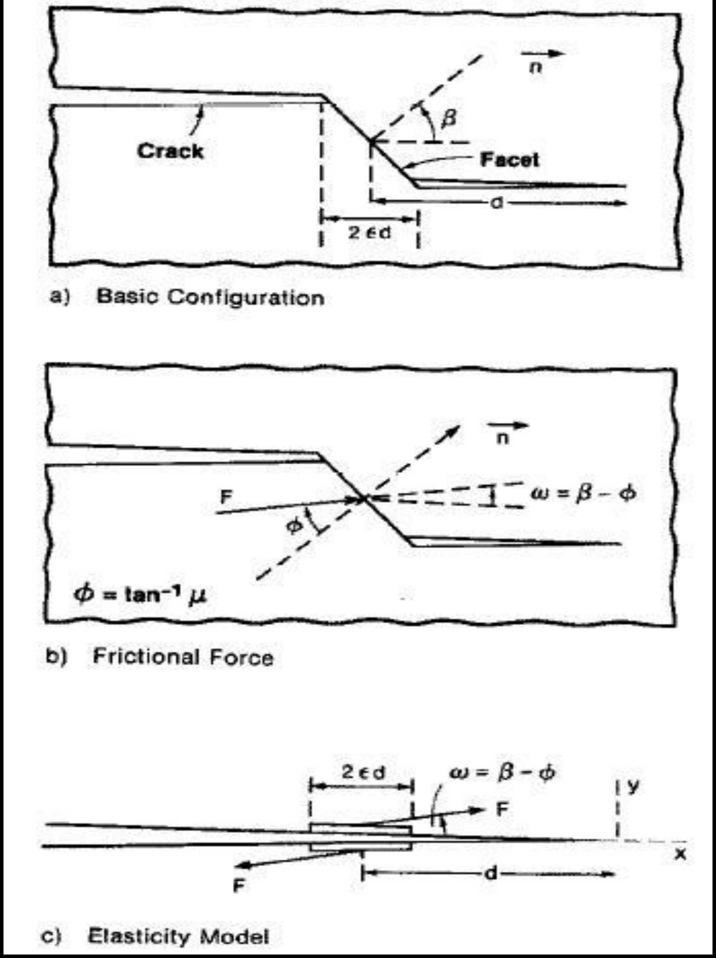
$$\frac{\Delta G}{G} \equiv \Sigma(\phi, \beta, \psi, \epsilon)$$

$$= + 2h \frac{[(\sin\beta + \cos\beta \tan\psi)(\sin(\beta - \phi) + \cos(\beta - \phi)\tan\psi)]}{\cos\varphi(1 + \tan^2\psi)}$$

$$- \frac{h^2(\sin\beta + \cos\beta \tan\psi)^2}{\cos^2\phi(1 + \tan^2\psi)}$$

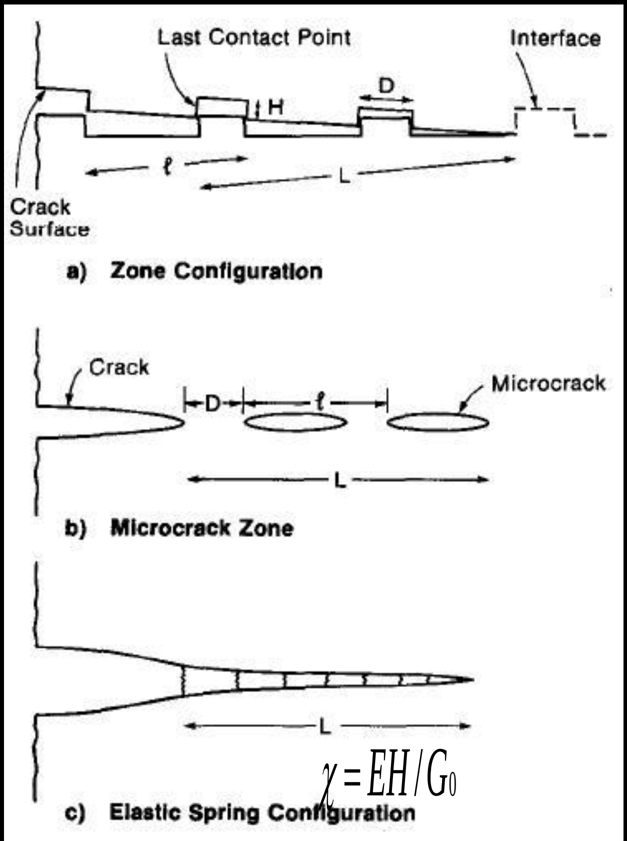
$\phi + \psi < \pi/2,$
$$\langle \Delta G \rangle / G = \frac{1}{\pi} \int_{\pi - \psi}^{\pi} \Sigma \, d\beta$$

$\phi + \psi > \pi/2$
$$\langle \Delta G \rangle / G = \frac{1}{\pi} \int_{\pi - \psi}^{3\pi/2 - \varphi - \psi} \Sigma \, d\beta + \left(\frac{\phi + \psi}{\pi} - \frac{1}{2}\right)(1 - \Omega).$$



Fundamental Mechanism of Interfacial Fracture

- *A zone model was proposed for improvement*



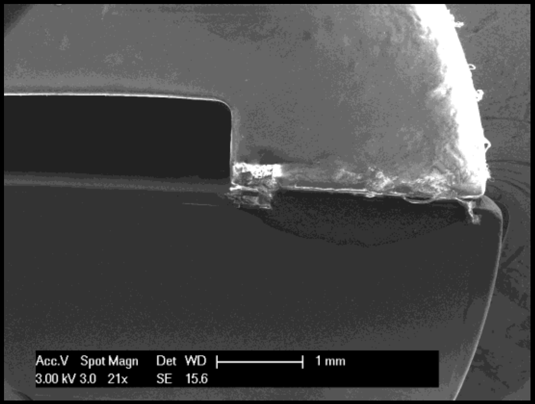
$$\alpha = \frac{(L/l)}{\ln[1/\sin(\pi D/2l)]}$$

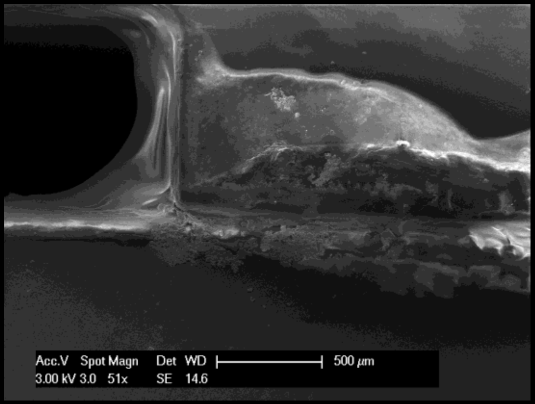
$$\alpha_0 = \frac{\pi(EH^2/lG_0)}{32(1-\nu^2)\ln[1/\sin(\pi D/2l)]}.$$

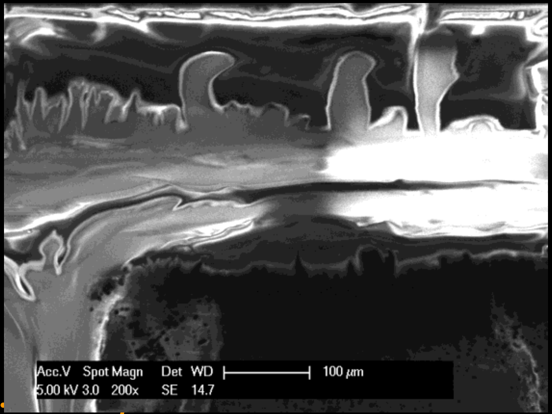
$$\Delta G/G = \frac{\tan^2\psi\{1 - k[\alpha_0(1+\tan^2\psi)(\Delta G/G + 1)]\}}{1+\tan^2\psi}.$$

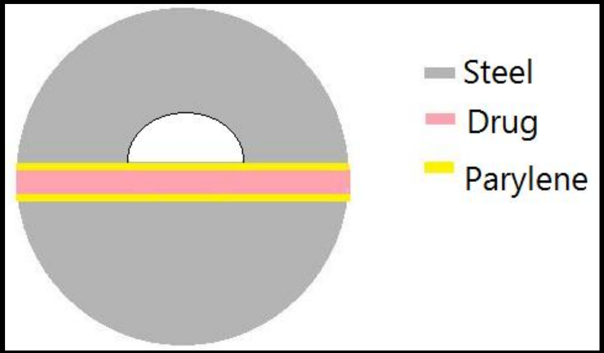
$$G_i = G_0(1+\tan^2\psi).$$

Crack Surface Profile Measurement





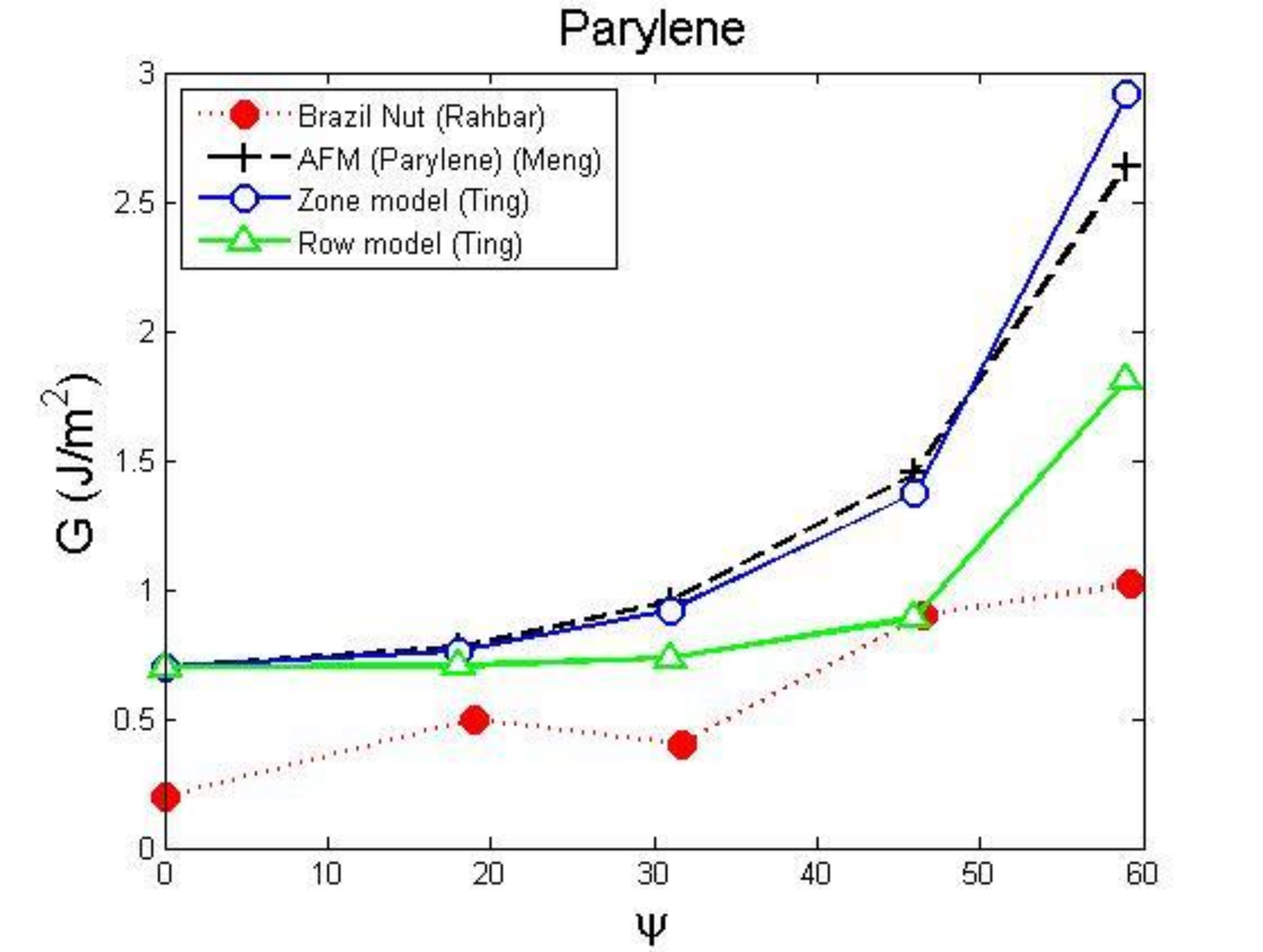




Material and Geometrical Parameters

Stainless Steel	*Interface*	*Parylene*	*Interface*	*Drug*
E=205GPa		*E=3GPa*		*E=2.1~3.7GPa*
v=0.3		*v=0.28*		*v=0.27*
	G_0=0.70N/m		*G_0=0.19N/m*	
	L=500um		*L=1500um*	
	l=100um		*l=50um*	
	D=20um		*D=6um*	
	H=10um		*H=3um*	

Comparison of Model Predictions



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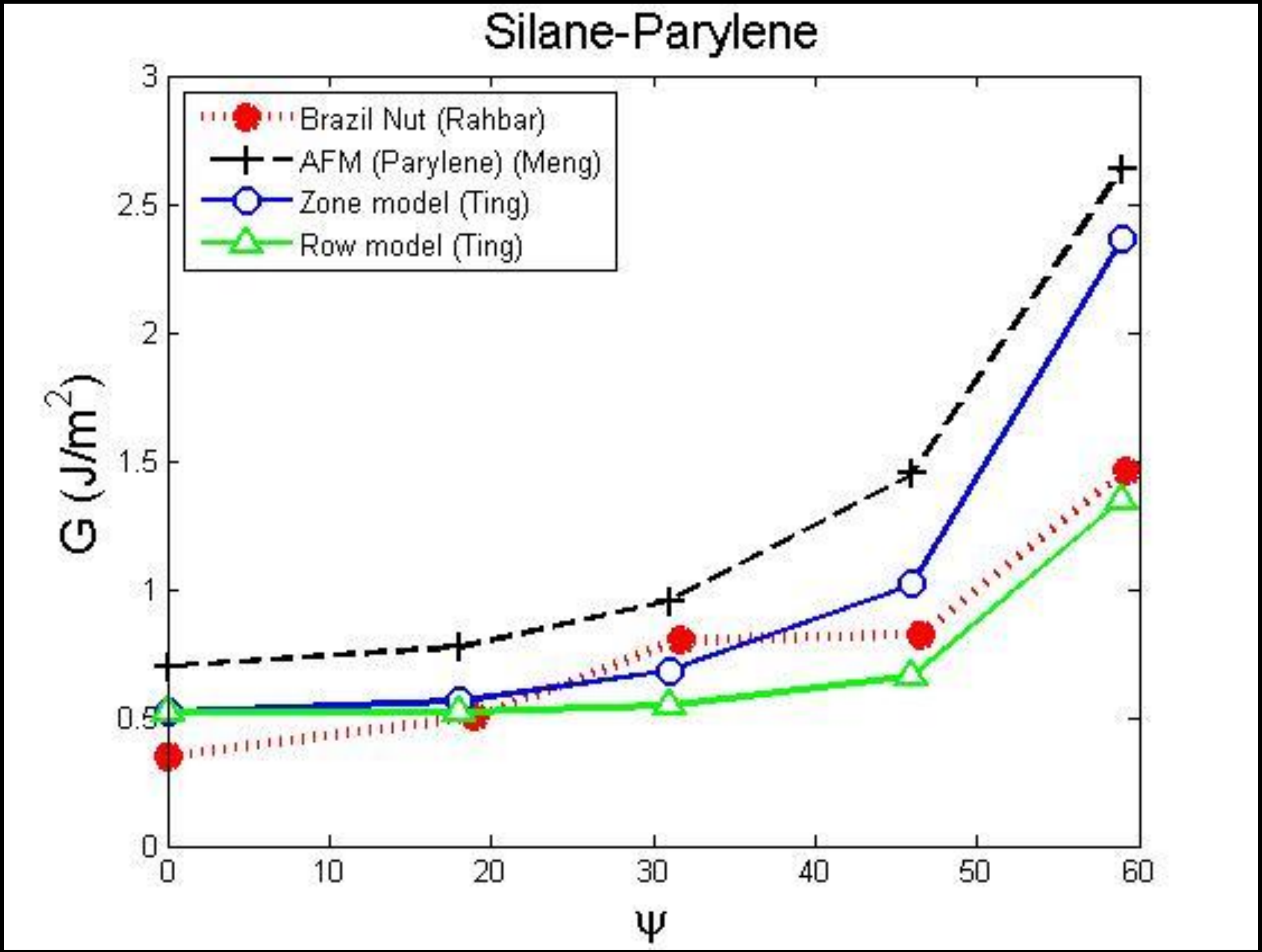
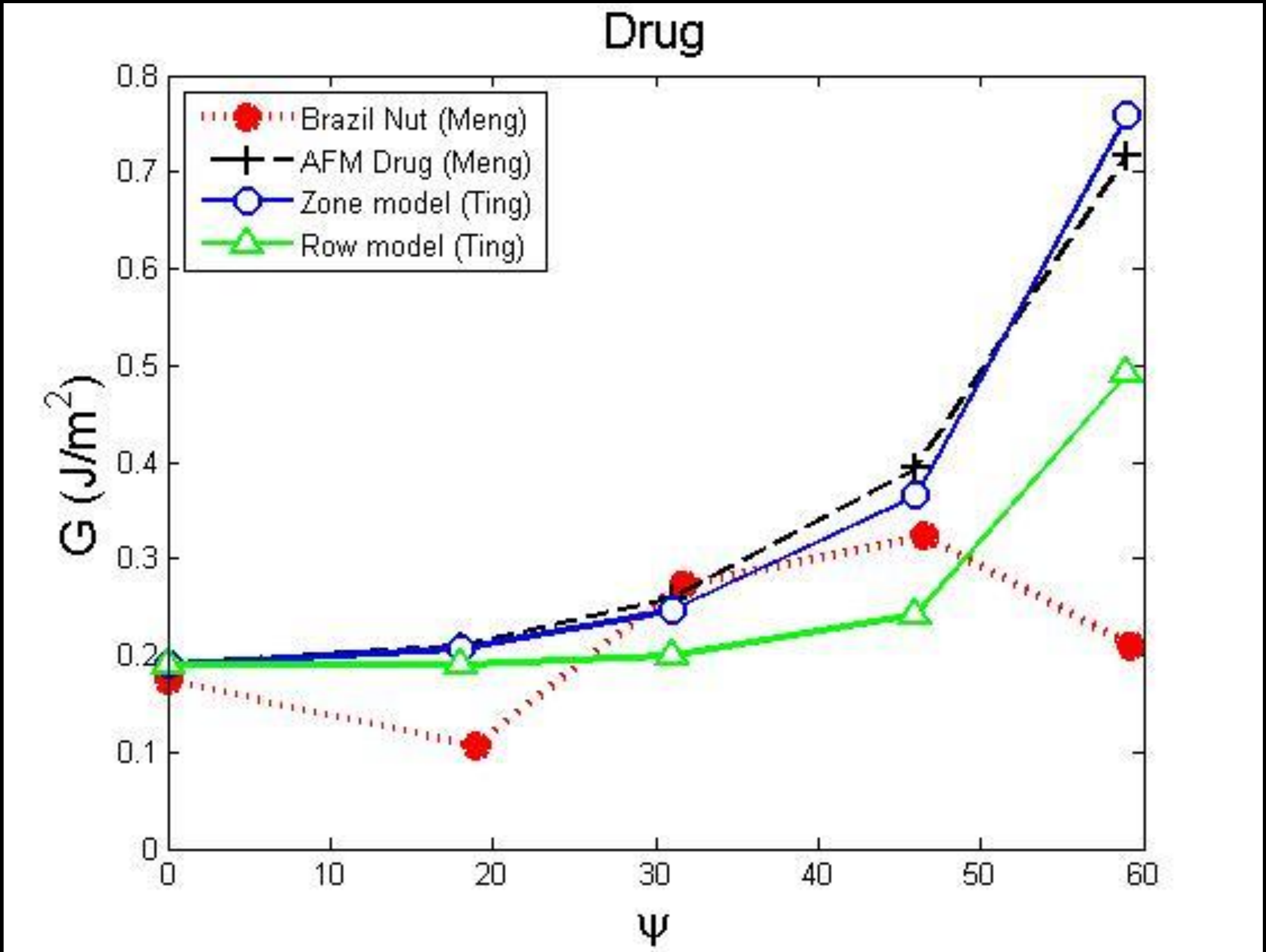


Comparison of Model Predictions



Summary and Concluding Remarks

- *This class presents some examples of the applications of adhesion and fracture mechanics concepts to drug eluting stents*
- *Pull-off forces determined from AFM experiments on bi-material pairs (useful for ranking interfaces)*
- *Brazil disk specimens used to measure mode mixity dependence of interfacial fracture toughness*
- *Link established between molecular AFM measurements of pull-off force and surface energy*
- *The surface energy estimates are in good agreement with results from Brazil disk tests*
- *Trends of mode mixity fracture toughness from row/zone models in agreement with experiments*

Acknowledgments

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- *George Papendreou*
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Overview of Course

- *Introduction to fatigue crack initiation and propagation*
- *Empirical fatigue models*
- *Fundamentals of fracture mechanics*
- *Toughening mechanisms*
- *Fundamentals of fracture – brittle/ductile and mechanisms in different classes of materials*
- *Frontiers of fracture mechanics – dental multilayers and biomedical stents*