Peak Stress Intensity Factor Governs Crack Propagation in Crosslinked UHMWPE

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Disclosures and Acknowledgements

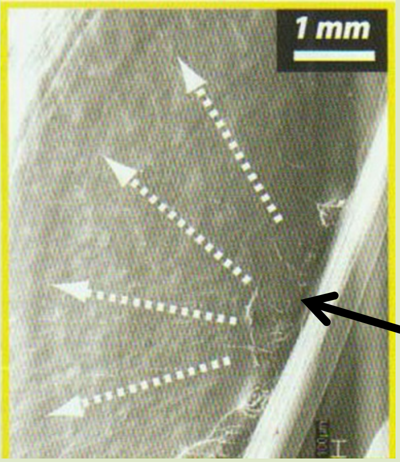
- NIH/NIAMS T32 AR00750 (JF)
- NIH/NIAMS R01AR047192 (CMR)

- Orthoplastics Ltd, Lancashire, UK
- Wilbert J. Austin Chair (CMR)
- Jay Bensusan M.S.(Experimental Assistance)

I have no potential conflicts with this presentation.

Introduction

- Failure as a result of crack propagation observed in recent studies of crosslinked UHMWPE acetabular components



Crack initiation site

J. Furmanski et al., Biomaterials 30 (2009) 5572-5582.

Tower SS et al., J Bone Joint Surg 89A (2010) 2212-2217.

Failure analysis of UHMWPE Components

- **Defect tolerant approach**
  - Accepts that cracks/flaws may be present in the structure
  - Crosslinking reduces fatigue crack propagation resistance

Baker et al., J. Biomed. Mat. Res. 66A 1:146-154

Medel el al., J. Biomed Mat Res 83B 2(2007)380-390

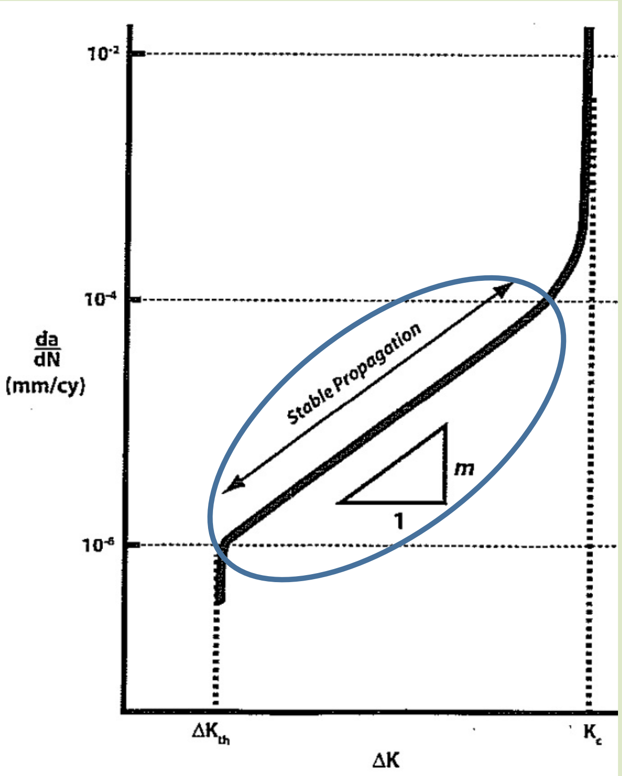
Fatigue Crack Propagation Analysis

- Defect tolerant approach utilizes LEFM
- P.C. Paris: Fatigue crack growth is driven by the range of stress intensity applied

$$\frac{da}{dN} = C\Delta K^m$$

C, m: Function of intrinsic

and extrinsic factors



Crack Growth Under Static or Creep Mode

- Peak stress intensity relationship

$$\frac{da}{dt} = YK_{\max}{}^{n}$$

- Analogous to Paris relationship
- Velocity of crack propagation is related to applied peak stress intensity rather than the range of stress intensity ΔK

Crack Growth Under Static or Creep Mode

- Fatigue damage vs damage as a result of peak stress in a cycle
  - Studied for HDPE and LDPE
  - Studies found that crack growth rate was driven by the duration of maximum load applied rather than the cyclic loading for HDPE and LDPE

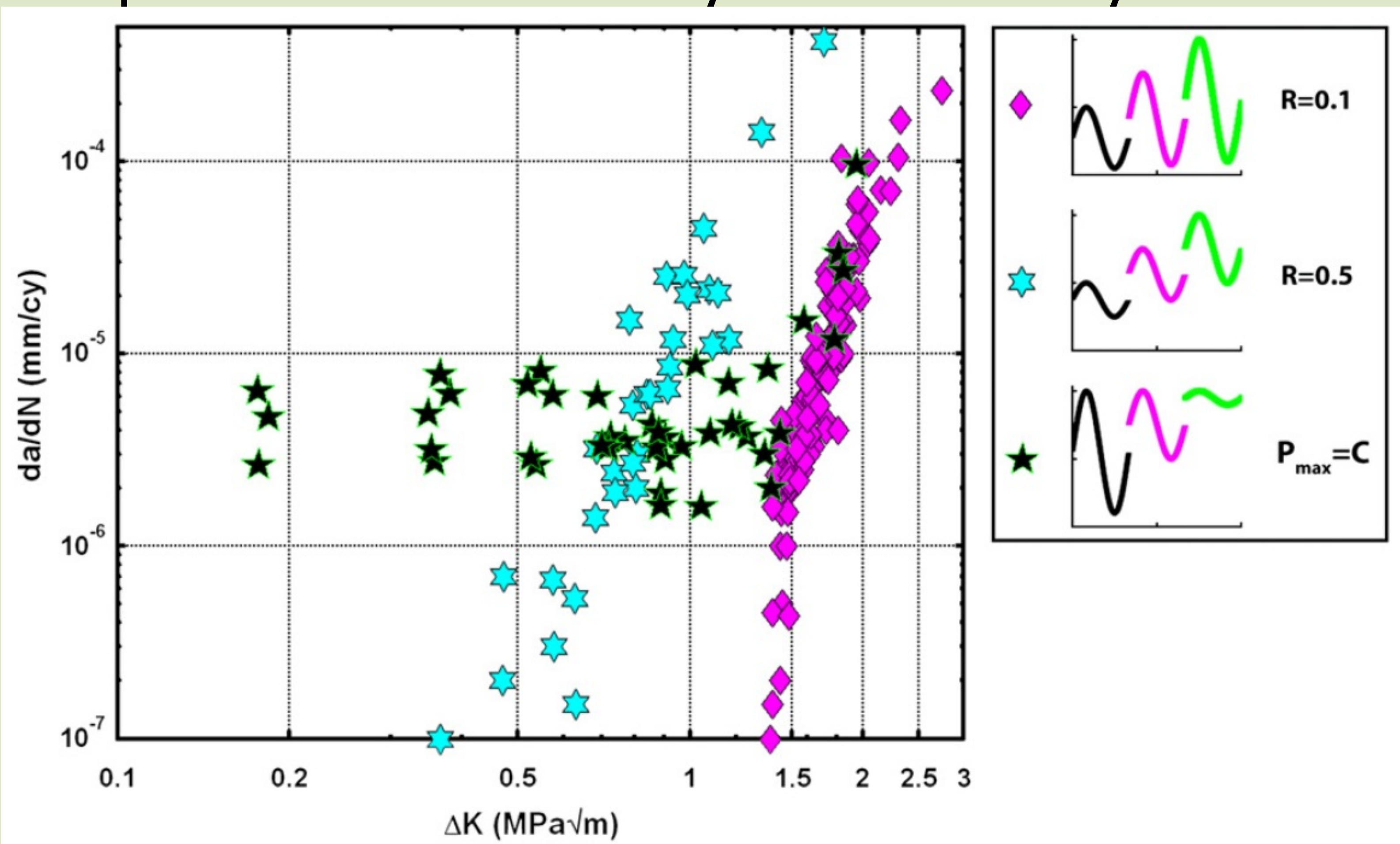
Dumpleton et al., Int J Fatigue 3(1987) 151-158.

Zhou and Brown., J Material Science 30(1995) 6065-6069

  - Studies found that resins have varying resistance to fracture for cyclic and static loading conditions

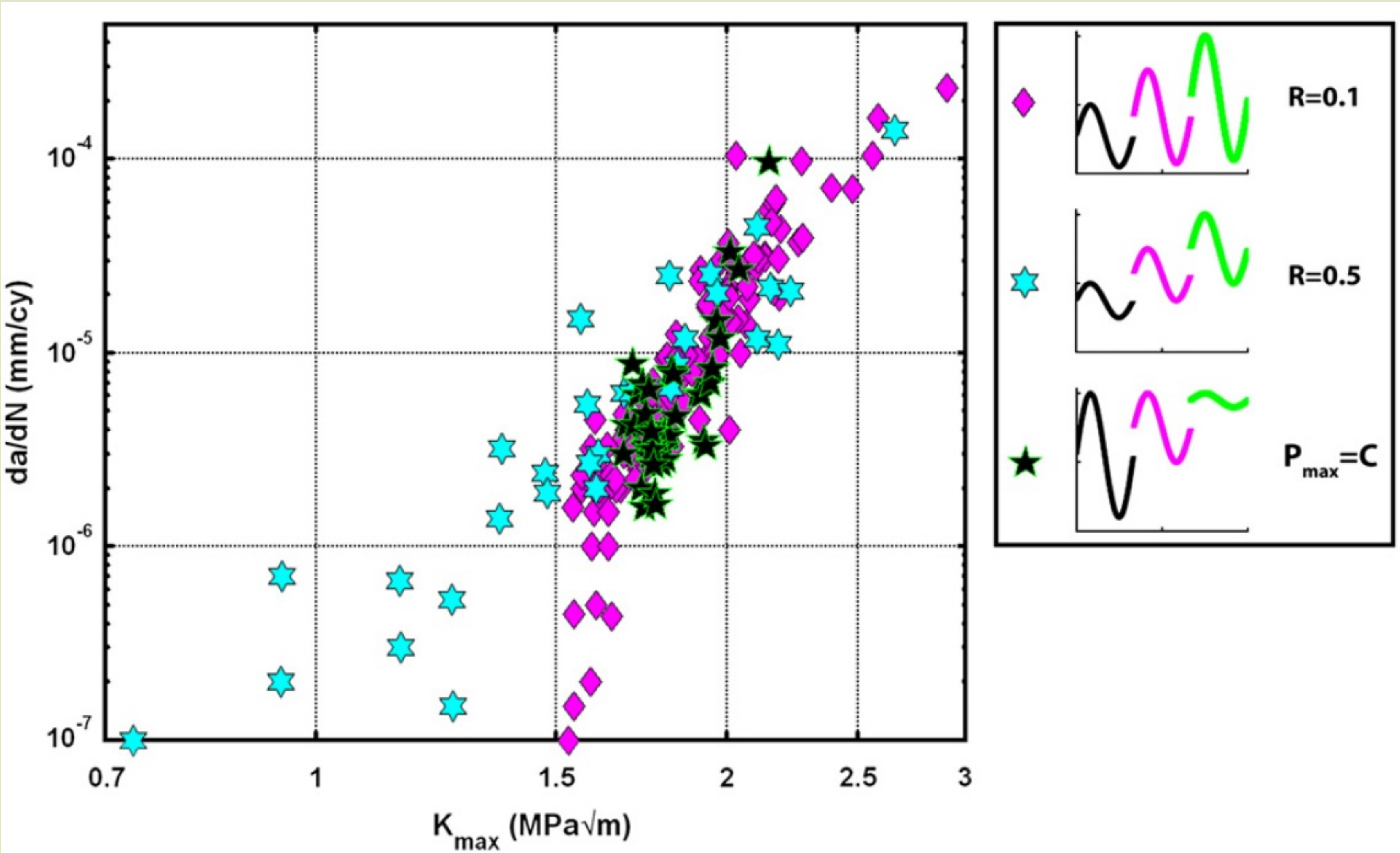
Static crack growth: Un-crosslinked UHMWPE

- Velocity of crack growth controlled by applied peak stress intensity factor in a cycle



J. Furmanski et al., Polymer 48(2007) 3512-3519.

Static crack growth: Un-crosslinked UHMWPE



J. Furmanski et al., Polymer 48(2007) 3512-3519.

Hypothesis

- The hypothesis of this study is that the crack propagation velocity of highly crosslinked UHMWPE is also driven by the peak stress intensity, K_{max}, during cyclic loading, rather than the stress intensity factor range, ΔK

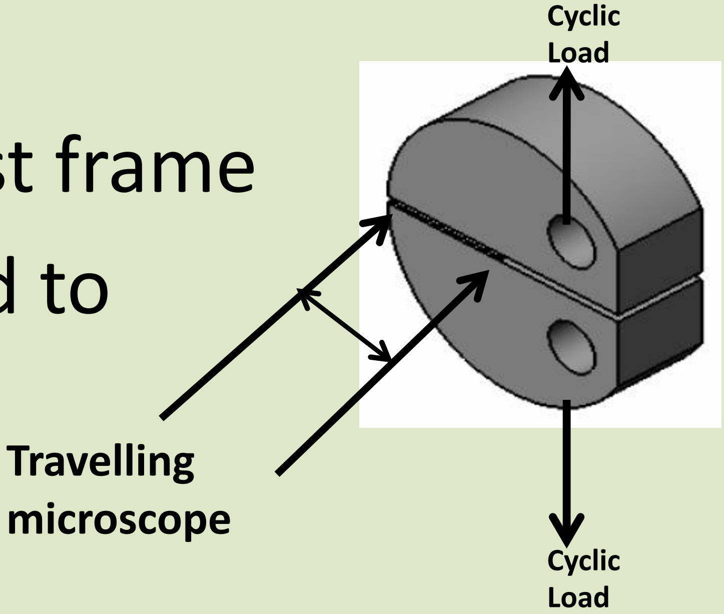
Materials

- Two crosslinked UHMWPEs (Orthoplastics, Ltd)
  - Remelted 65 kGy
  - Remelted 100 kGy
- Ram extruded rod
- Stored in freezer
  - To minimize oxidation

  [Kurtz SM et al., J Arthroplasty; 2003; 18 (7);68-78.]

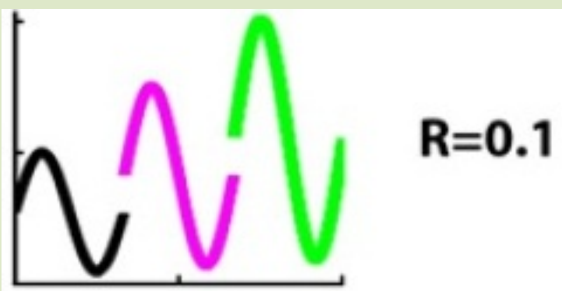
Methods

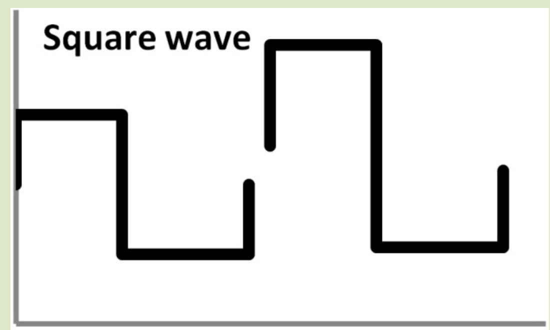
- Round compact tension specimens
  - w=40 mm, b=20 mm, a=17 mm,
  - side grooves= 2mm
- Fatigue crack propagation tests conducted following ASTM E-647-11
  - Instron servo-hydraulic test frame
  - Travelling microscope used to measure the crack growth
    - 5 micron resolution



Test Design

- Four conditions designed to test the hypothesis:
  - Square wave R=0.1, frequency f = 1 Hz (n=2)
  - Sine wave R=0.1, frequency f = 0.1 Hz (n=2)
  - Sine wave R=0.5, frequency f = 3 Hz (n=2)
  - Sine wave R=0.1, frequency f = 5 Hz (n=2)





Test Design

- The conditions were selected to obtain data in different regions in the space of Paris relationship

- Different R-ratios were designed to get the material response for higher applied constant stress intensity

- Two different waveforms were implemented to demonstrate that the crack growth can be predicted by applying a scaling factor for different waveforms

Data Analysis

- da/dN versus ΔK
  - Two point method to calculate da/dN
  - ΔK was calculated based on the applied load using the ASTM standard E-647-11
- da/dt versus K_{max}
  - The applied frequency was multiplied with the da/dN data to obtain the da/dt

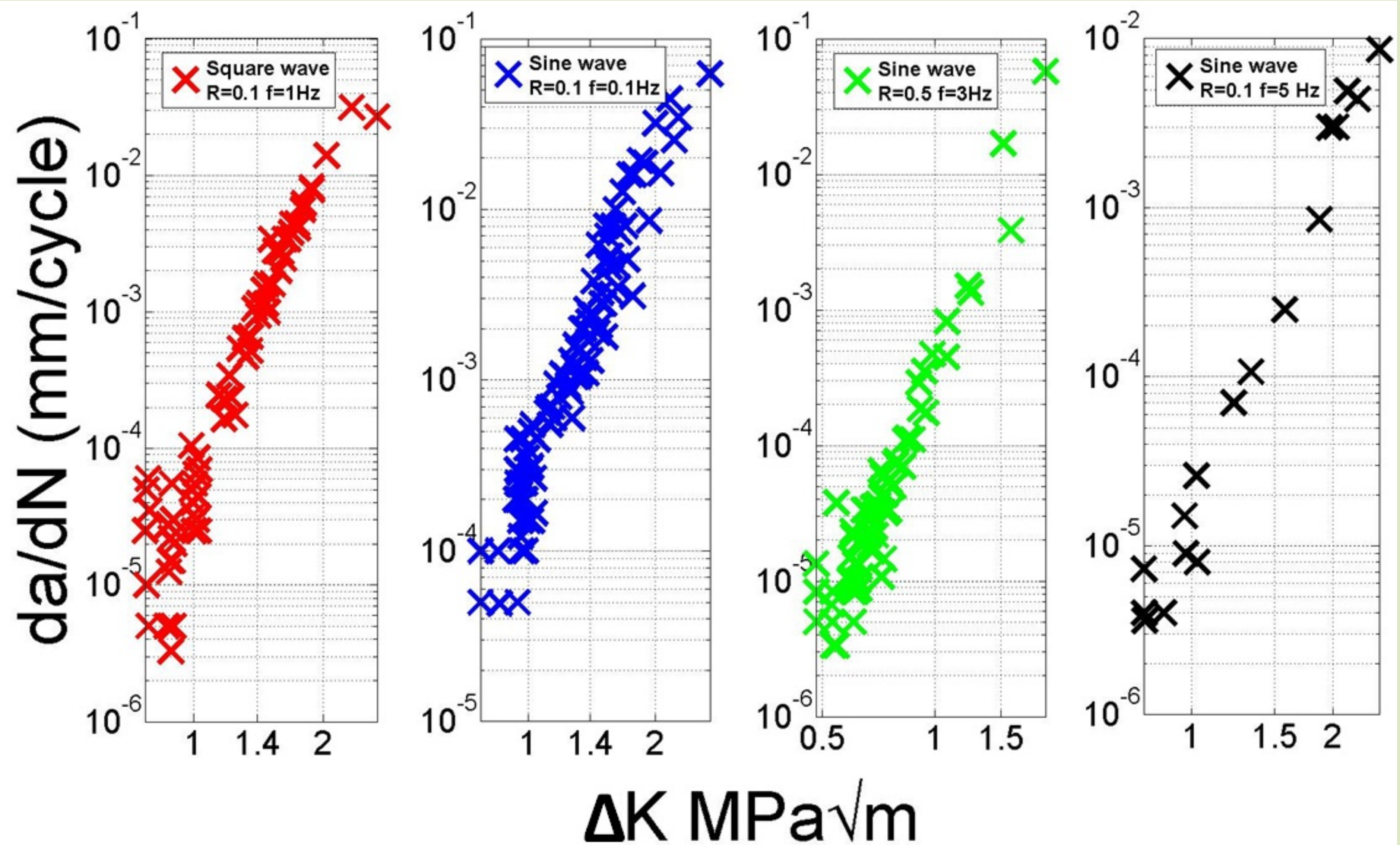
Data Analysis

- Average velocity normalizing factor (Q) obtained

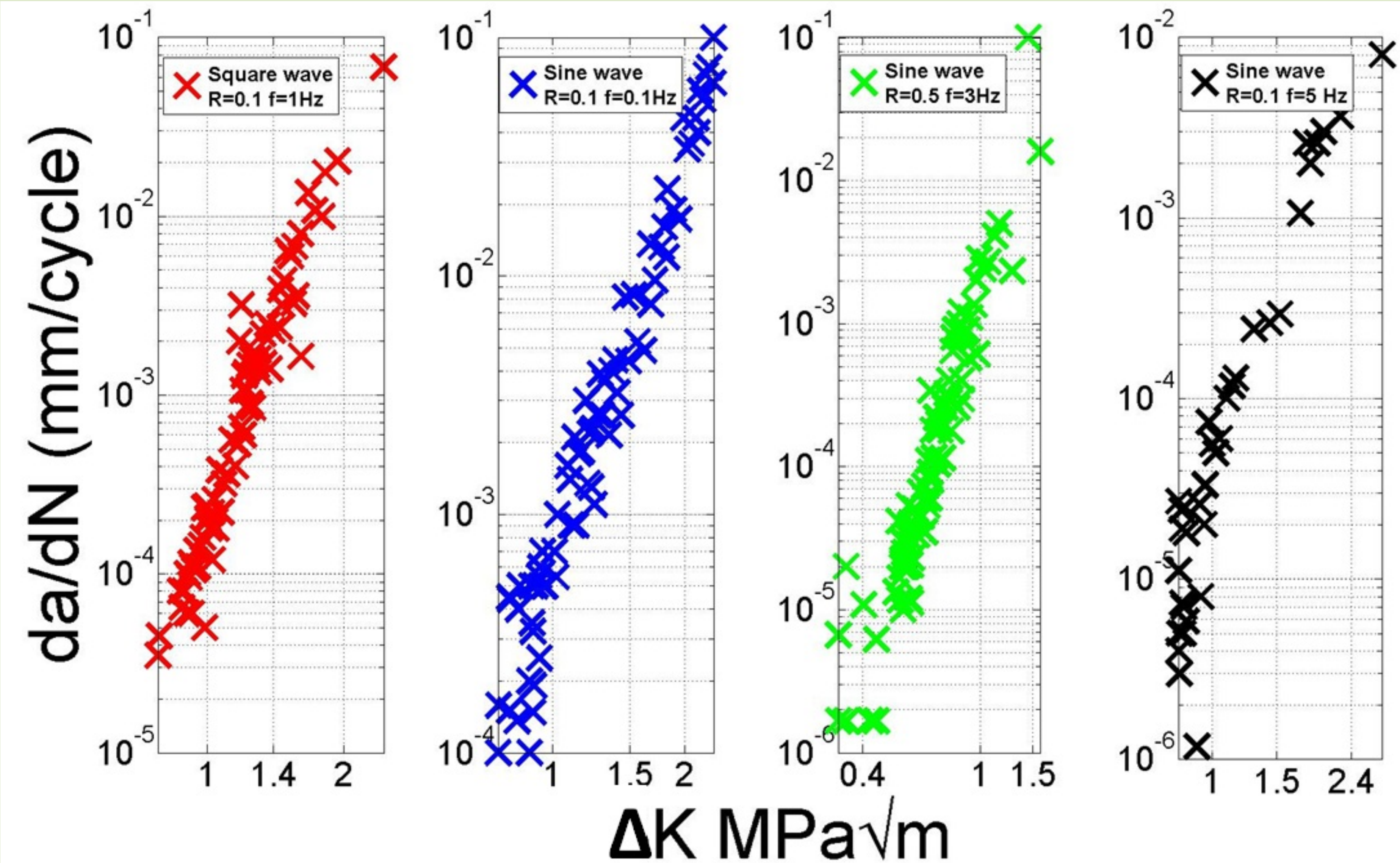
- $Q = \frac{\Delta a_{square}}{\Delta a_{sine}} = \frac{\int_0^\lambda (K_{(t)square})^n dt}{\int_0^\lambda (K_{(t)sine})^n dt}$

- Data integrated from instantaneous load values obtained at 500 Hz through a LabView program

Results-Remelted 65 kGy

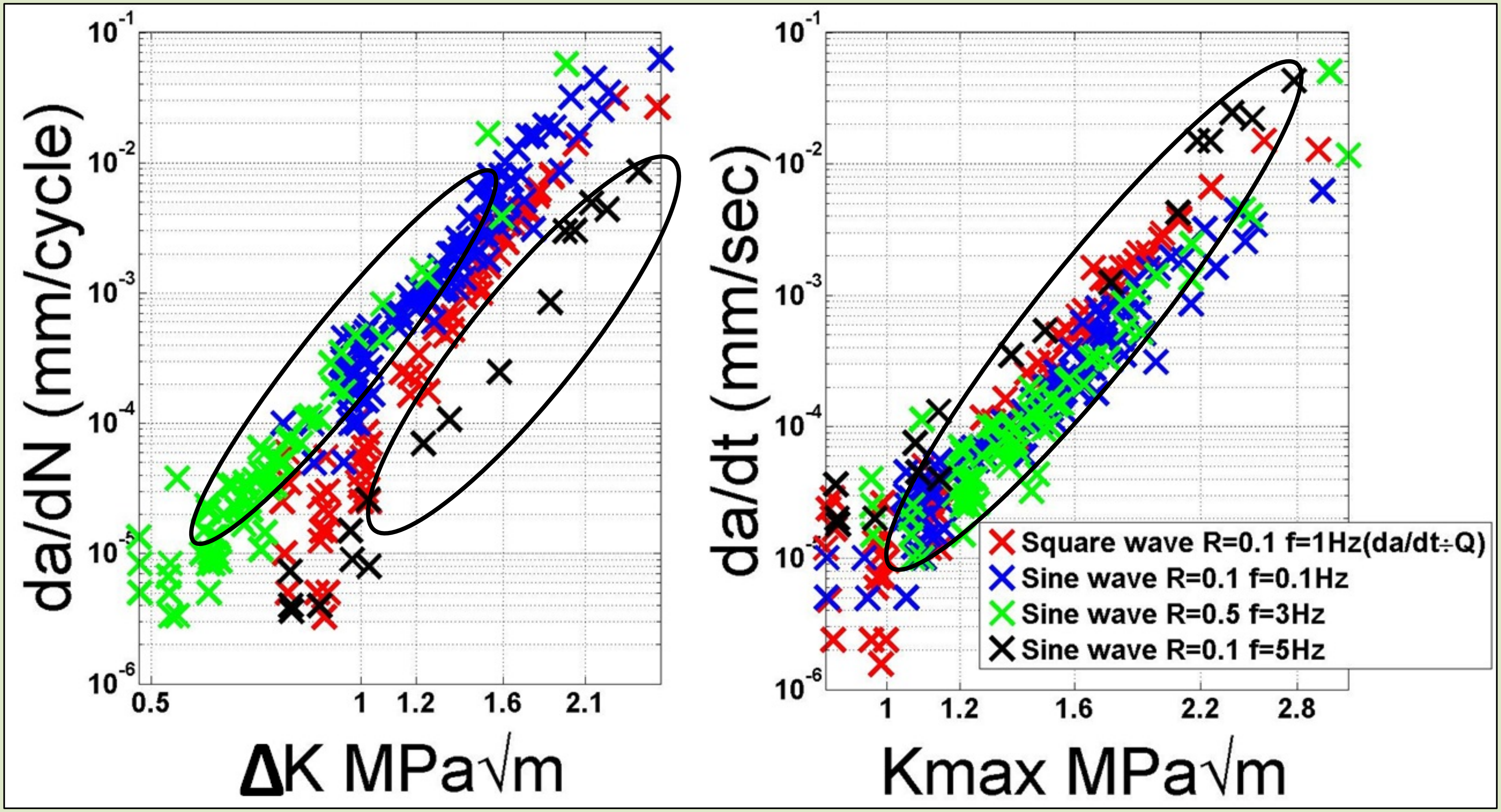


Results-Remelted 100 kGy



Results-Peak Stress Relationship

- Remelted 65 kGy – Peak stress governs crack growth



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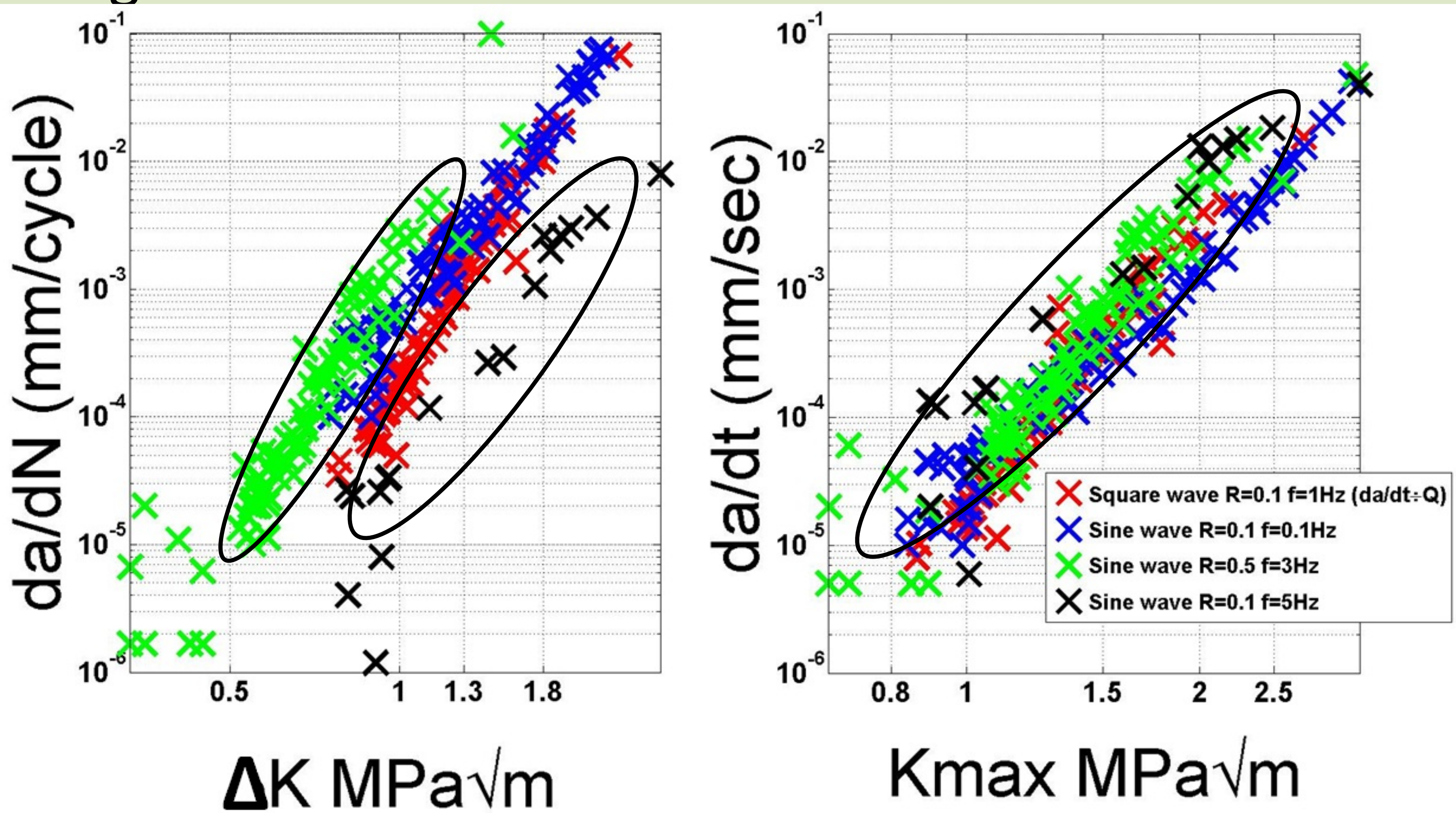

Results-Velocity Normalizing Factor

- Remelted 65 kGy

$$Q = \frac{\Delta a_{square}}{\Delta a_{sine}} = \frac{\int_0^{\lambda} \left(K_{(t)square}\right)^n dt}{\int_0^{\lambda} \left(K_{(t)sine}\right)^n dt} \approx 2.8$$

- Remelted 100 kGy

$$Q = \frac{\Delta a_{square}}{\Delta a_{sine}} = \frac{\int_0^{\lambda} \left(K_{(t)square}\right)^n dt}{\int_0^{\lambda} \left(K_{(t)sine}\right)^n dt} \approx 2.1$$

Results

- Constants from Paris relationship and Peak stress relationship

Testing Conditions	Remelted 65 kGy				Remelted 100 kGy			
	m	C(mm/cy)/(MPa√m)	n	Y(mm/sec)/(MPa√m)	m	C(mm/cy)/(MPa√m)	n	Y(mm/sec)/(MPa√m)
Square wave, f = 1 Hz, R =0.1	7.64	$7.0x10^{-5}$	7.64	$3.1x10^{-5}$	7.26	$2.1x10^{-4}$	6.81	$5.7x10^{-5}$
Sine wave, f = 0.1 Hz, R=0.1	6.00	$2.8x10^{-4}$	5.95	$1.6x10^{-5}$	5.22	$6.4x10^{-4}$	5.44	$3.8x10^{-5}$
Sine wave, f = 3 Hz, R=0.5	5.81	$3.6x10^{-4}$	5.70	$1.9x10^{-5}$	6.10	$1.5x10^{-3}$	6.80	$4.2x10^{-5}$
Sine wave, f = 5 Hz, R=0.1	7.35	$1.3x10^{-5}$	7.35	$3.0x10^{-5}$	5.31	$5.4x10^{-5}$	5.31	$1.6x10^{-4}$

- Both C and Y constants suggest that remelted 100 kGy is less resistant to crack propagation than remelted 65 kGy material

Discussion

- The hypothesis of the study is supported because the results suggest that for these two formulations of crosslinked UHMWPE, stable crack growth under cyclic loading is dependent on K_{max} and not ΔK
- This work is consistent with earlier work reported for non-crosslinked conventional UHMWPE material where it was found that crack growth was dependent on K_{max} and is governed by quasi-static driving forces
- The velocity scaling factor for square wave supports the theory that crack propagation is a time dependent phenomenon

J. Furmanski et al., Polymer 48(2007) 3512-3519.

Discussion

- Ductile fracture is associated with materials that exhibit crack propagation as a result of applied range of stress intensity ΔK

- Brittle fracture is associated with materials that exhibit crack propagation as a result of maximum applied stress intensity (K_{max})

- The results suggest that crosslinked UHMWPE should be treated as material failing in a brittle manner when it comes to fracture mechanics

Limitations

- Only two R-ratios were tested for the hypothesis, no negative R-ratios were tested or the effect of compressive loads were not studied
- Two crosslinked UHMWPE formulations were tested in the study, only remelted material was studied

Conclusion

- In the presence of a flaw or a design stress concentration region, the findings suggest that stable crack propagation can occur as a result of only static loading on UHMWPE joint replacement components. This should be taken into consideration while design of components.