Fatigue Property Mapping
Know Your Material

Endurica
Get Durability Right®

Elastomer Fatigue Property Mapping – Testing Service

Before Endurica, the fatigue analysis of elastomers was famously tricky. The *Fatigue Property Mapping*™ characterization protocols systematically measure the factors that govern durability. The resulting engineering parameters are ready to use with durability simulation codes including Endurica CL™, Endurica DT™, Endurica EIE™, and fe-safe/Rubber™. These powerful and efficient tests show how your rubber part endures under realistic operating conditions. Begin with the Core Fatigue and Hyperelastic modules, then add on the items you need to get the physics just right in your analysis.

Core Fatigue Module
Fully relaxing behavior from both nucleation and fracture mechanical perspectives

Hyperelastic Module
Simple, planar, and equibiaxial tension, Mullins effect

Intrinsic Strength (>10^6 cycles) Module
Quantify endurance limits

Thermal Module
Quantify dissipative properties, thermal properties

Non Relaxing Module
Quantify strain crystallization, minimum and mean strain effects

Cyclic Softening Module
Quantify cyclic softening effects

Extended Life (>10^6 cycles) Module
Quantify endurance limit, estimate aging rate of stiffness, intrinsic and ultimate strength

Reliability Module
Weibull statistics for strength and crack precursor size populations

Creep Module
Creep crack growth rate effects

Ozone Module
Quantify ozone attack critical energy and rate

Follow the instructions in this document to submit your material(s) and place your order for characterization.

Fatigue Property Map Prices

December 2022 | Pricing subject to change.

Item	Description	Price

Stress-Strain Behavior

Item	Description	Price
FPM-H	**Hyperelastic Module** • Required as a prerequisite to Finite Element Analysis • Lab ambient temperature (23°C) Deliverables Experiments: • simple tension, slow cyclic loading, raw data • planar tension, slow cyclic loading, raw data • biaxial tension, slow cyclic loading, raw data Analysis and Reporting: • Identification of a suitable hyperelastic function and parameters for FEA • Identification of parameters for specifying Mullins effect in ABAQUS, ANSYS or MARC • Unit cube validation and stability check	$2,100
FPM-HV	**Volumetric Compression Add-on to Hyperelastic Module** • Useful for specifying dilatational behavior of elastomers in highly confined deformation states. Recommended when p / K > 5%.	$475
FPM-H-TEMP	**Temperature Upcharge for non 23°C Hyperelastic Module** • Indicate temperature with range of -40°C to 150°C	$925

Fatigue Behavior

Item	Description	Price
FPM-C	**Fully Relaxing Fatigue - Core Module** • Required for all fatigue analyses • Lab ambient temperature (23°C) • Fully relaxing (R = 0) conditions for all fatigue tests Deliverables Experiments: • static tearing raw data • fatigue crack growth raw data (20 hour procedure) • cyclic simple tension to rupture raw data • cycles to failure tensile raw data, 2 strain levels Analysis and Reporting: • critical tearing energy T_c • tensile strain, stress, energy at break • fatigue crack growth rate curve and its parameters (r_c, and F) • crack precursor size (c_0) calculation and sensitivity analysis • strain-life, stress-life, and energy-life fatigue curves	$7,750
FPM-CORE-TEMP	**Temperature Upcharge for non 23°C Core Module** • Indicate temperature with range of -40°C to 150°C	$1,400

FPM-IS **Intrinsic Strength Module** $2,445

- Recommended for cases with fatigue life longer than 10^6 cycles

Deliverables

Experiments	Analysis and Reporting
• cutting force raw data, 3 strain levels	• cutting vs. tearing curve • intrinsic strength T_0 • fatigue threshold strain, stress, energy (if ordered with FPM-C)

FPM-NR **Non-relaxing Fatigue Module** $3,000

- Recommended for cases where fatigue loading is never fully relieved to zero
- Lab ambient temperature (23°C)
- Test is run under a range of nonrelaxing (R > 0) conditions
- Note: It is required to run FPM-C in order to run this Module.

Deliverables

Experiments	Analysis and Reporting
• raw data from fatigue crack growth arrest procedure with minimum strain sweep	• strain crystallization functions $F(R)$ and $x(R)$ • Haigh diagram showing sensitivity to minimum strain of crack nucleation life

FPM-NR-TEMP **Temperature Upcharge for non 23°C Non-Relaxing Module** $850

- Indicate temperature with range of -40°C to 150°C

FPM-RL **Reliability Module** $3,450

- Recommended when probability of failure needs to be estimated.
- Testing is run at room temperature: 23°C.
- If ordered with FPM-C, includes analysis of strain life curve dependence on probability of occurrence.

Deliverables

Experiments	Analysis and Reporting
• 50 simple tension pull to failure experiments • Static tearing, 3 replicates	• Summary statistics for pull to failure (strain, stress, energy at break) • Calculation of crack precursor size distribution c0 • Weibull analysis parameters relating frequency of occurrence to size of crack precursor

FPM-TB **Thermal Effects Module - Basic** $4,995

- Always recommended for cases with self-heating or thermal gradients
- User gives 2 (additional to FPM-C) temperatures between -40°C & 150°C
- *Note: It is required to run FPM-C in order to run this Module.*

Deliverables

Experiments	Analysis and Reporting
• static tearing raw data at 2 temperatures • cyclic stress strain raw data at 1 temp., 1 frequency, 5 strain levels	• heat generation law parameters describing dependence of hysteresis on strain • tear strength vs. temperature

FPM-TX	**Advanced Effects Add-on to Thermal Module** • For highest accuracy in structural and heat transfer analyses of self-heating and thermal gradient effects. • FPM-TB is required as prerequisite. Deliverables *Experiments* • static tearing raw data at 2 more temperatures • cyclic stress strain raw data at 3 temperatures and 3 frequencies • thermal conductivity, specific heat & density measurements • thermal expansion measurement *Analysis and Reporting* • heat generation law parameters describing dependence of hysteresis on strain, rate, and temperature • tear strength vs. temperature • fatigue crack growth rate law temperature sensitivity coefficient • coefficient of thermal expansion		$9,975

Ageing Effects

FPM-AB	**Ageing Module - Basic** • Recommended for cases with fatigue life longer than 10^6 cycles, and when ageing must be taken into account for a specific aged condition. • Note: It is required to run FPM-IS in order to run this Module. Deliverables *Experiments* • ageing in oven at 1 client-specified time and temperature • static tearing raw data, unaged vs. aged • cutting force raw data, unaged vs. aged *Analysis and Reporting* • cutting vs. tearing curve, unaged vs aged • intrinsic strength T_0, unaged vs aged • tearing energy T_c, unaged vs aged • fatigue threshold strain, stress, energy, unaged vs aged (when ordered with FPM-C)		$4,975
FPM-AM	**Ageing Module – 3x3 matrix / Master Curve** • Recommended for cases with fatigue life longer than 10^6 cycles, and when ageing must be taken into account. • Note: It is required to run FPM-IS in order to run this Module. Deliverables *Experiments* • ageing in oven at 3 temperatures for 3 time periods: 3 days, 10 days, 30 days • static tearing raw data, 3 ageing periods x 3 ageing temperatures • cutting force raw data, 3 strain levels x 3 ageing periods x 3 ageing temperatures *Analysis and Reporting* • cutting vs. tearing curve at each aged condition • intrinsic strength T_0 vs. ageing master curve • tearing energy T_c vs. ageing master curve • Arrhenius activation energy, E_a • fatigue threshold strain, stress, energy vs. ageing curves (when ordered with FPM-C) • parameters specifying ageing time and temperature dependence of T_0 and T_c • extrapolation of ageing effects to longer timescales for an application-specific temperature		$22,495

Other Effects

FPM-CCG	**Elastomer Fatigue Property Map – Creep Crack Growth Module** • Recommended for cases involving long periods under static load • Lab ambient temperature (23°C) Deliverables Experiments: • raw data from quasistatic creep crack growth procedure Analysis and Reporting: • Creep crack growth rate curve and its parameters (T_q, r_q, and F_q)	$1,615
FPM-CCG-TEMP	**Temperature Upcharge for non 23°C Creep Crack Growth Module** Indicate temperature with range of -40°C to 175°C	$850
FPM-S	**Elastomer Fatigue Property Map – Cyclic Softening Module** • Recommended for cases where stiffness degradation limits durability • Lab ambient temperature (23°C) Deliverables Experiments: • raw data from cyclic softening procedure on simple tension strips at 5 strain levels Analysis and Reporting: • Family of cyclic softening curves showing stiffness degradation rate as a function of life consumed • Curve fit to cyclic softening model	$2,845
FPM-S-TEMP	**Temperature Upcharge for non 23°C Cyclic Softening Module** Indicate temperature with range of -40°C to 175°C	$750
FPM-OZ	**Elastomer Fatigue Property Map – Ozone Effect Module** • Required when rubber that has a susceptibility to ozone attack is operating in an environment with ozone • Default exposure: 50 pphm O_3 concentration, 72 hrs @ room temperature 23°C Deliverables Experiments: • Images of crack development on specimen • 3 replicates Analysis and Reporting: • Determine $\mathcal{E}_z$ - critical strain • Determine r_z - ozone crack growth rate • Determine T_z - critical energy for ozone attack	$950

Ordering Instructions:

1) Send **Purchase Order** specifying number of materials and tests to be run, and the email address to which results should be delivered, to:

   Endurica LLC
   jasuter@endurica.com
   1219 West Main Cross, Suite 201
   Findlay, OH 45840
   USA
   Phone: +1-419-957-0543

2) Test specimens are die-cut from customer-provided sheets of approximate dimensions 150 mm x 150 mm x 1-2 mm. Please see the **Fatigue Property Map Material Shipment Form** on the following page for the number of material slabs to send to Axel Products, Inc.

   a. Label each slab with the material identifier you want us to use in reporting.

   b. Complete the **Fatigue Property Map Material Shipment Form** for each material and include it with your material samples.

3) Test execution times may vary, depending on lab backlog and Modules requested. Once testing, analysis and reporting are complete, you will receive an email from Endurica containing the analysis and summary report, and all raw data files.

Notes:

All results delivered via email. The raw data is delivered in an ASCII format.
The analysis and summary report is delivered in PDF format.

Customer data and materials will be retained for 1 year after initial data delivery.

Purchase Order, VISA, MasterCard, AMEX, and Discover Card are accepted methods of payment.

Terms: NET 30 Days after Delivery of Final Report and Data.

Fatigue Property Map Material Shipment Form

****Include one form for each material in your shipment****

1) Check the items being requested, and complete the customer specs:

✓	Item	Module	Customer Specifications	Slabs*
	FPM-H	Hyperelastic	Peak strain levels: Temperature:	4
	FPM-HV	Volumetric Compression		1
	FPM-C	Core Fatigue Testing	Test Temp: Test Freq:	5
	FPM-IS	Intrinsic Strength		3
	FPM-NR	Nonrelaxing	Test Temp: Test Freq:	1
	FPM-RL	Reliability		10
	FPM-TB	Thermal – Basic	Test Temps (2):	3
	FPM-TXA	Thermal - Advanced	Test Temps (3): Frequencies (3):	3
	FPM-AB	Ageing - Basic	Aged / Unaged	5
	FPM-AM	Ageing – Master Curve	Ageing Oven Temps (3):	30
	FPM-CCG	Creep Crack Growth	Test Temp:	1
	FPM-S	Cyclic Softening	Test Temp:	1
	FPM-OZ	Ozone Effect	O_3 Concentration: Test Temp: Time:	1
			Total Slabs Sent	

Customer Notes:

* Nominal slab dimensions are 150 mm x 150 mm x 2 mm.

2) Attach a business card or write the contact information of the person responsible for specifying this testing.

3) Ship samples to:

Endurica LLC
Attn. Joe Suter
1219 West Main Cross, Suite 201
Findlay, OH 45840
USA

Analysis and Summary Report Examples

Fatigue Property Mapping – Hyperelastic Module Example Results (FPM-H)

The Hyperelastic Module produces the basic information about nonlinear stress-strain behavior that is needed to obtain a hyperelastic model for use with FEA, and to represent the cyclic softening (Mullins effect) in the FE model.

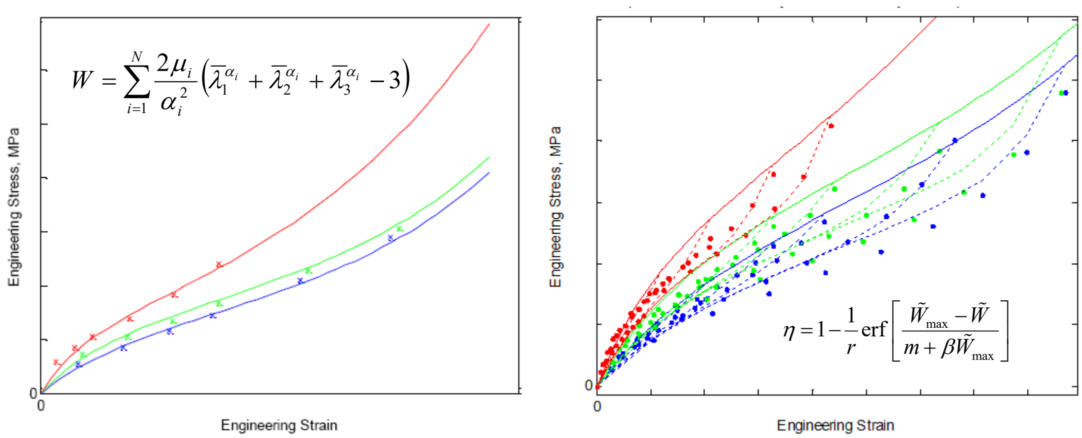


Figure 1. The lefthand plot shows typical hyperelastic law fit to stress-strain curves measured in simple (blue), planar (green) and equibiaxial (red) tension. Observations are shown with symbols, best fit with solid lines. The righthand plot shows typical Mullins law fit to cyclic stabilized stress-strain curves.

Fatigue Property Mapping – Core Module Example Results (FPM-C)

The Core Module gives the basic fatigue crack growth rate curve (Figures 2 and 3), as well as the strain-life curve and crack precursor size (Figure 4). This module is a pre-requisite for any fatigue analysis.

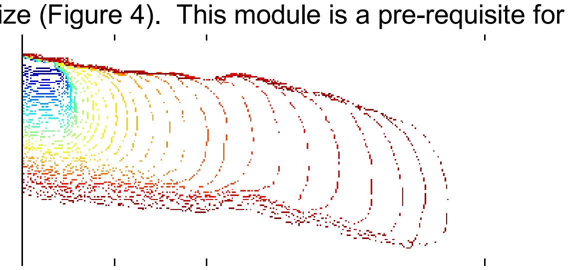


Figure 2. Typical crack tip images collected during fatigue testing. Each contour represents the crack tip shape at a given number of cycles. Colors indicate time, with blue at the beginning of the test, and deep red at the end.

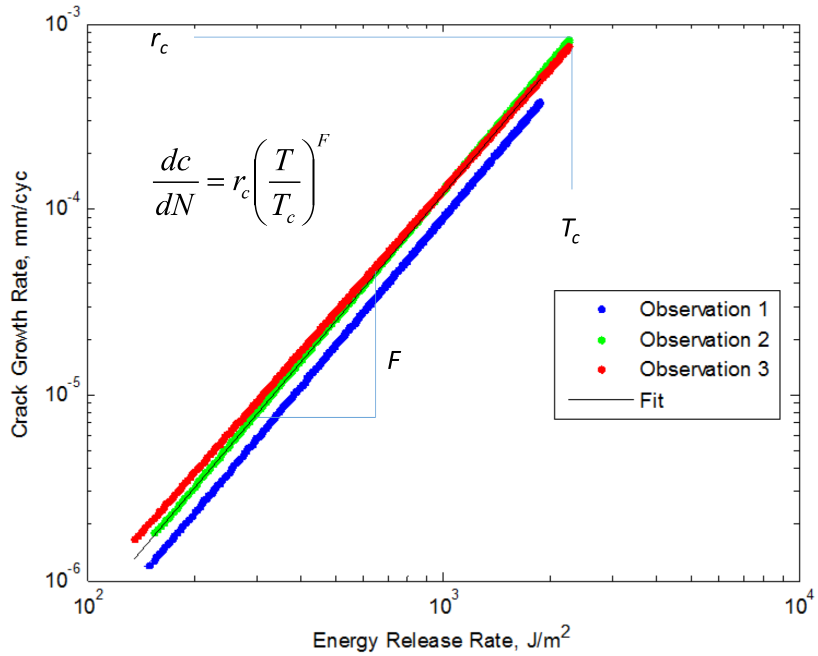


Figure 3. Fatigue crack growth rate observations and model fit parameters.

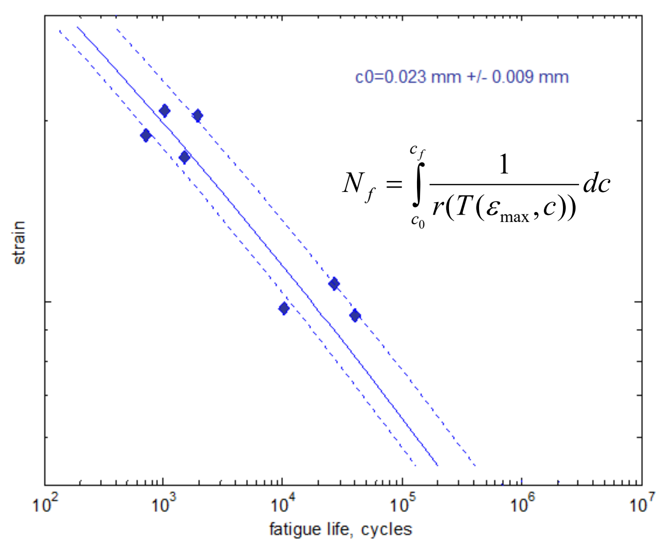


Figure 4. Crack nucleation experiments overlaid with computed strain-life curve corresponding to crack precursor size c_0. Dotted lines show the effect of crack precursor size variation on the strain-life curve.

Fatigue Property Mapping – Intrinsic Strength Module Example Results (FPM-IS)

This module measures the material's intrinsic strength – the minimum energy release rate required to produce crack growth. Because operation below this limit does not supply sufficient energy to grow a crack, the intrinsic strength is also called the endurance limit. Use this module when the material is expected to serve for a very large number of cycles.

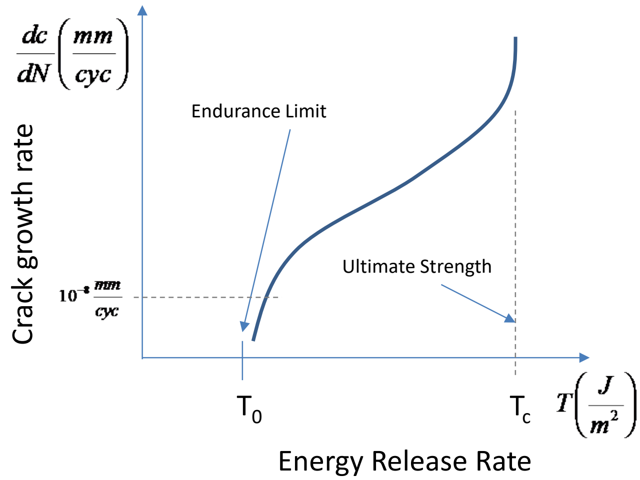


Figure 5. The fatigue endurance limit T_0 is the highest energy release rate that can be carried without incurring fatigue crack growth. Its value reflects the intrinsic strength of the polymer chains that must be broken in order to propagate a crack. It is measured via cutting experiments with a highly sharpened, instrumented microtome blade.

Fatigue Property Mapping – Nonrelaxing Module Example Results (FPM-NR)

Under nonrelaxing loads, some elastomers exhibit enhanced fatigue life / slowed crack growth due to strain crystallization effects. The effect is measured using crack arrest experiments in which a crack growing initially under fully relaxing loads is gradually operated under increasingly nonrelaxing loads. By observing the kinetics of crack arrest, a great deal can be learned about how the effect is impacting fatigue performance. This information is required when constructing rubber's Haigh diagram for a crystallizing material.

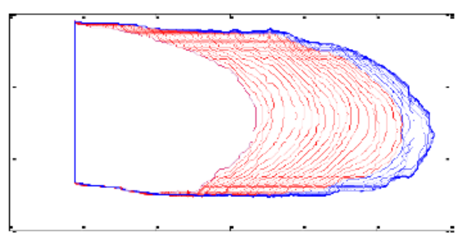


Figure 6. Crack tip images obtained during crack arrest experiments. Red images show the crack tip while growing under fully relaxing conditions. Blue images show the crack tip while growing under nonrelaxing conditions.

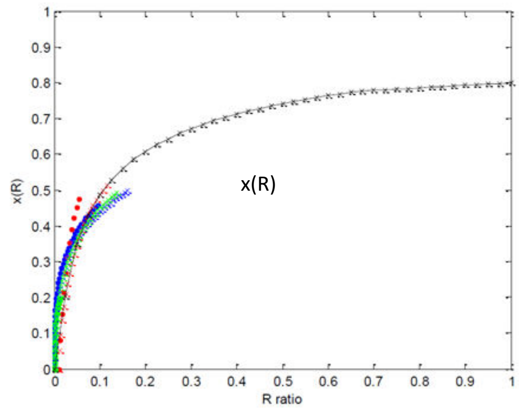


Figure 7. Typical strain-crystallization function $x(R)$, showing dependence on the degree of nonrelaxation ratio R = Tmin / Tmax (where Tmin and Tmax are the energy release rate cycle extremes).

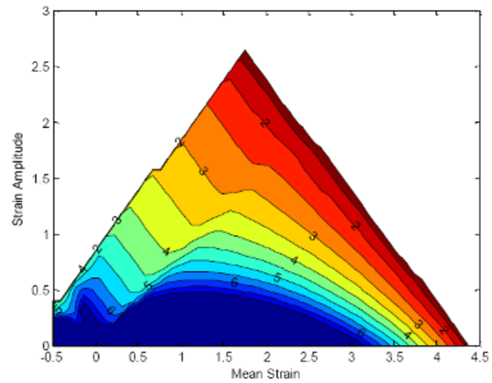


Figure 8. Typical Haigh diagram for simple tension/compression loading, computed based on crack growth measurements and crack precursor size inferred from nucleation experiments. Contours are colored and labeled according the base 10 logarithm of the fatigue crack nucleation life.

Fatigue Property Mapping – Reliability Example Results (FPM-RL)

The Reliability Module characterizes the rate of occurrence of crack precursors of a given size. This information is useful for estimating likely strength or fatigue failure rates for quality/warranty applications.

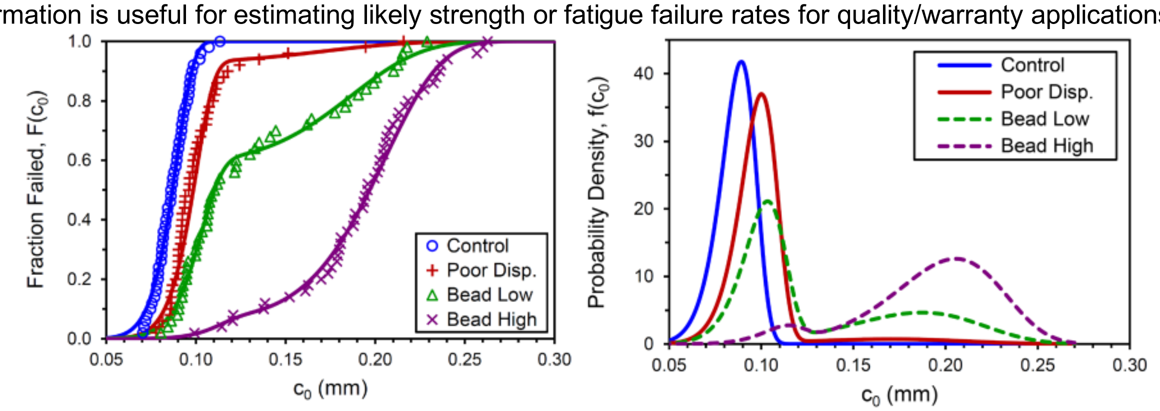


Figure 9. Typical Weibull analysis results showing cumulative and probability density distributions for crack precursor size.

Fatigue Property Mapping – Thermal Module Example Results (FPM-TH)

The thermal modules produce information useful for cases involving significant self-heating and/or thermal gradients.

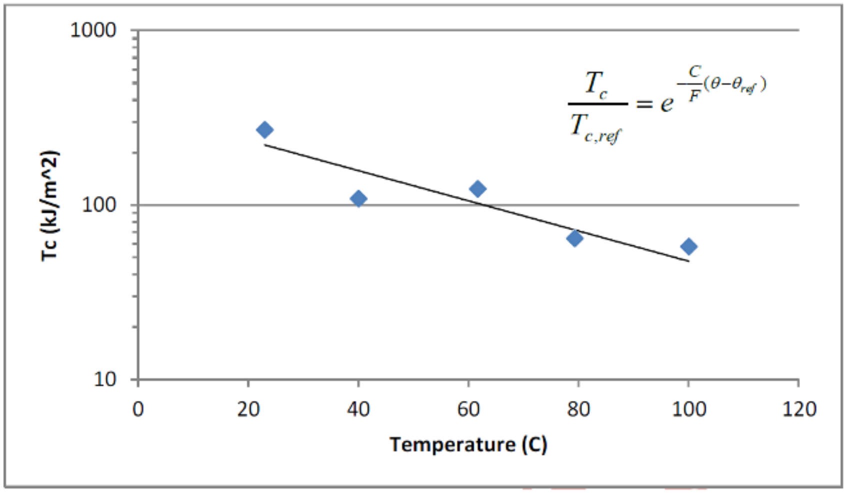


Figure 10. Dependence of tearing energy T_c on specimen temperature.

Fatigue Property Mapping – Extended Life Module Example Results (FPM-EL)

The extended life module is recommended when the material operates below the endurance limit. Although cracks may not grow due to mechanical fatigue, the material properties may still evolve with exposure to heat history. A series of oven ageing experiments is used to develop master curves showing the evolution of stiffness, intrinsic strength, and fracture strength with time. The protocol also produces an estimate of the activation energy of the Arrhenius rate law describing the time-temperature dependence of ageing in the material.

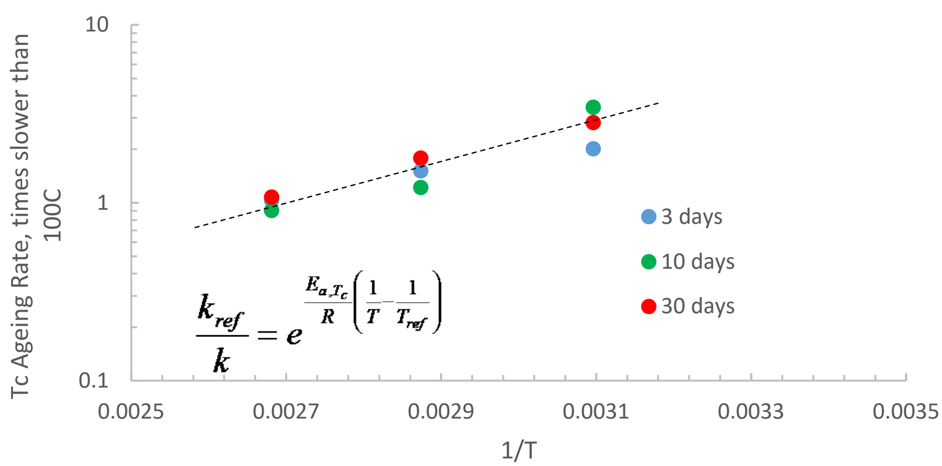


Figure 11. Determination of ageing rate dependence on time and temperature.

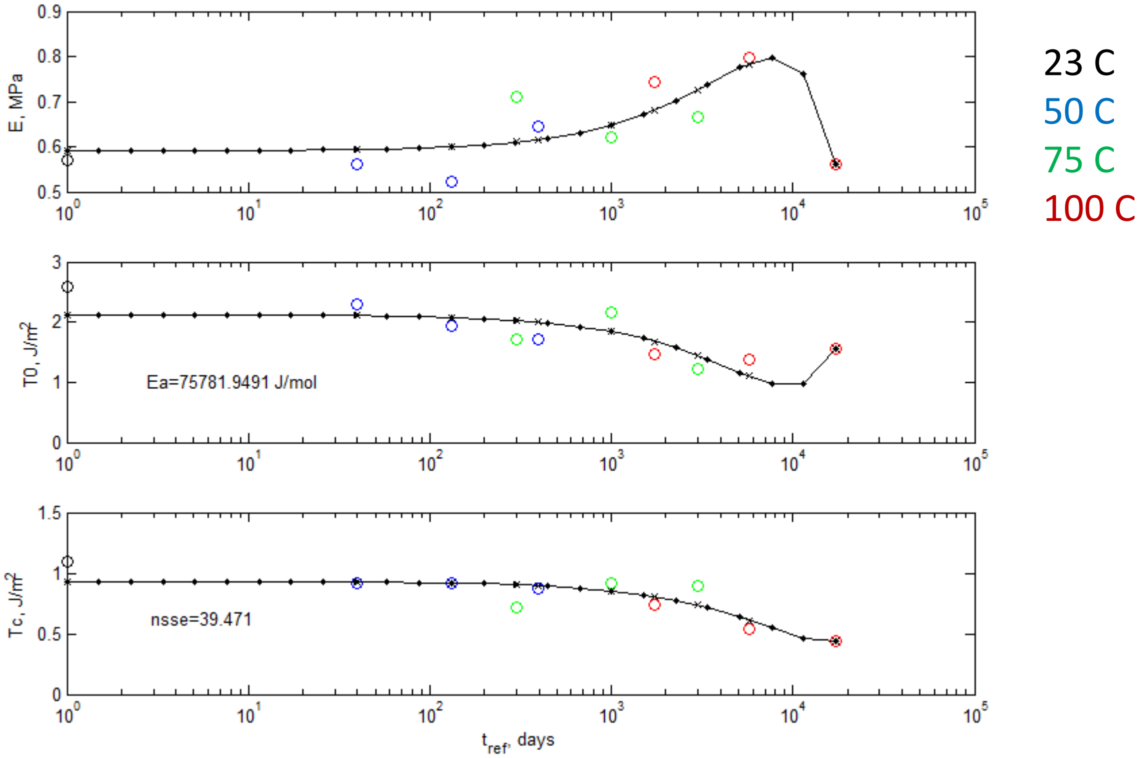


Figure 12. Ageing experiments over a 3x3 matrix of oven temperature and time settings are used to develop accelerated degradation curves. Based on the Arrhenius rate law, the accelerated degradation curves are compiled into a master curve for a specific reference temperature (here, the reference temperature is 23° C).

Fatigue Property Mapping – Creep Crack Growth Example Results (FPM-CCG)

The creep crack growth rate module produces information useful for cases involving long-term static loads under which time-dependent crack growth (rather than cycle-dependent crack growth) may occur.

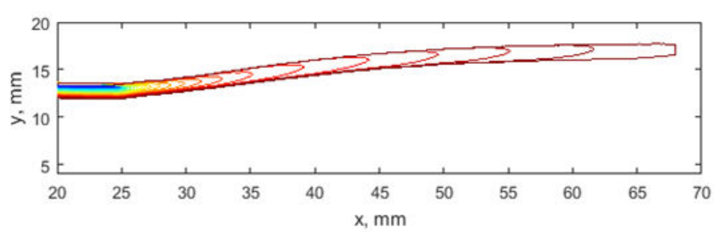


Figure 13. Typical crack tip images collected during fatigue testing. Each contour represents the crack tip shape at a given number of cycles. Colors indicate time, with blue at the beginning of the test, and deep red at the end.

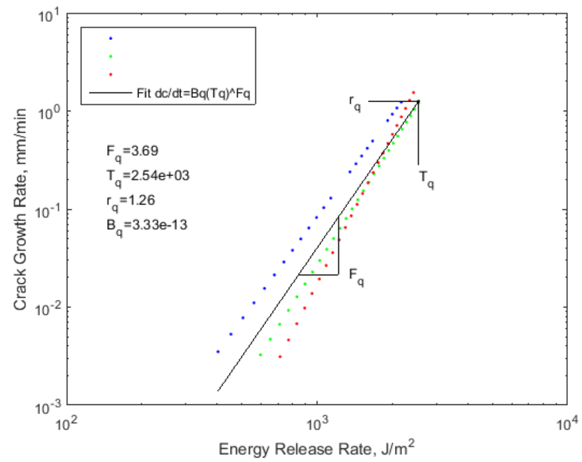
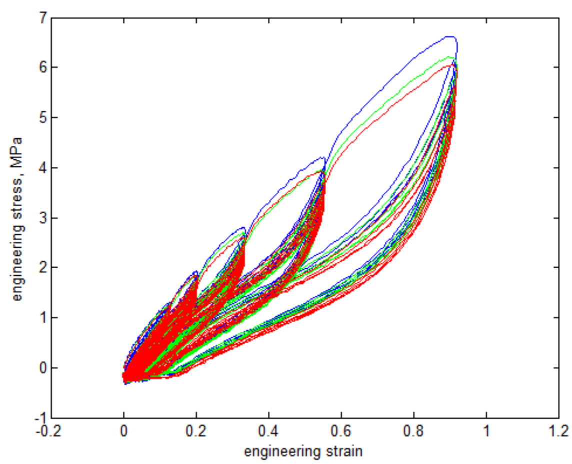


Figure 14. Fatigue crack growth rate observations and model fit parameters.

Fatigue Property Mapping – Cyclic Softening (FPM-S)

The cyclic softening module produces information about the rate at which stiffness evolves under cyclic solicitations. This information is useful for modeling stiffness evolution under fatigue cycles using Endurica DT's stiffness loss cosimulation feature. The experiment is run in displacement control, and it records the evolution of the peak stress with cycles.



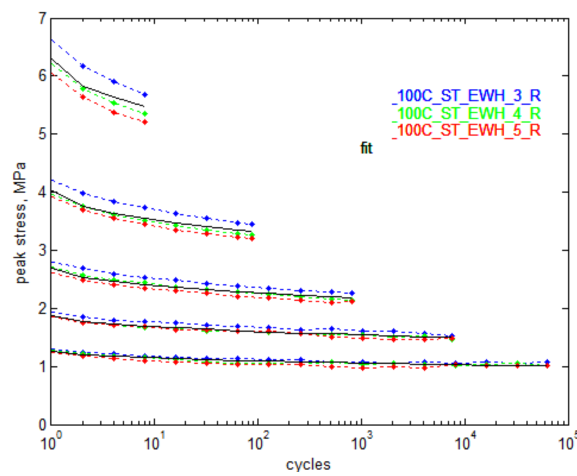


Figure 15. Cyclic softening stress-strain response (left), and evolution of peak stress at 5 different strain levels.

Fatigue Property Mapping – Ozone Effect (FPM-OZ)

Ozone is a trace gas that strongly reacts with some rubbers to produce surface cracking following exposure. Ozone cracking can limit useful product life, even when mechanical cycles operate below the mechanical fatigue threshold. The Endurica ozone attack testing method determines: ε_z the critical strain for ozone attack; T_z the critical tearing energy for ozone attack; and r_z the rate of crack growth due to ozone attack.

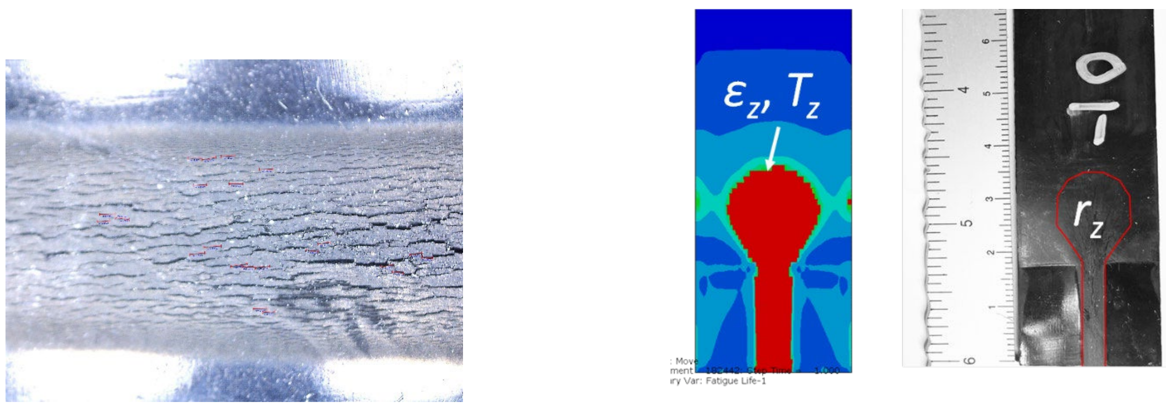


Figure 16. Typical surface cracking after ozone attack (left). Simulated ozone cracking pattern (middle). Actual ozone cracking pattern (right).

About Our Fatigue Property Mapping Service

The service enables engineers to obtain, from a commercial source, highly reliable, affordable measurements suitable for use in fatigue analysis.

Training on the experimental procedures and analysis for fatigue life prediction is available. For complete information and our schedule of upcoming classes please visit www.endurica.com/training2/

About Endurica

Endurica LLC develops the world's most versatile and best-validated fatigue life simulation system for elastomers. Through our technology and services, Endurica empowers our clients' analysis of the real-world fatigue performance of elastomers at the design stage, when the greatest opportunity exists to influence performance, and before investment in costly fatigue testing of prototypes. Endurica was founded in 2008 and received the 2020 Tibbetts Award for outstanding cutting-edge technology by the United States Small Business Administration. www.endurica.com

About ACE Laboratories

The talented team of professionals at ACE Laboratories provides independent analytical and physical testing services. ACE's 200,000 square-foot, state-of-the-art, ISO/IEC 17025 accredited polymer testing laboratory is staffed by experienced technicians boasting over 200 years of combined industry experience in their professional journey to set new standards in the testing industry. https://www.ace-laboratories.com/

About Axel Products

Founded in 1994, Axel Products provides testing services for engineers and analysts with a focus on the characterization of nonlinear materials such as elastomers and plastics. Data from the Axel laboratory is often used to develop material models in finite element analysis codes such as ABAQUS, Ansys, fe-safe/Rubber, Hexagon (MSC/Marc), and LS-Dyna. Testing services are also provided to examine sealing and fatigue problems, long-term thermal mechanical testing, and high strain rate testing. www.axelproducts.com