Fatigue Property Mapping
Know Your Material

Endurica
Accelerating Reliable Design

Elastomer Fatigue Property Mapping – Characterization Service

Fatigue of elastomers is governed by many factors. The *Fatigue Property Mapping*™ family of characterization protocols systematically inventories these factors. The result is a set of engineering parameters that can be used with durability simulation codes, such as Endurica CL™ and fe-safe/rubber™, to determine how fatigue performance depends on the complex conditions that are encountered by a part in service. The protocols are organized into a set of Modules, with each Module focused on a typical design/analysis task, so that it is easy to select which protocols are needed in a given program.

Hyperelastic Module
Simple, Planar, and Equibiaxial tension, Mullins Effect

Core Fatigue Module
Fully Relaxing Behavior from both nucleation and fracture mechanical perspectives

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

Nonrelaxing Module
Quantify Strain Crystallization, Min and Mean Strain Effects

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

Thermal Module
Quantify dissipative properties, thermal properties, temperature dependence

Creep Module
Quantify Creep Crack Growth Rate Effects

Cyclic Softening Module
Quantify Cyclic Softening Effects

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

Fatigue Property Map Prices

August 2016. Pricing subject to change.

Item	Description	Price
FPM-C	**Elastomer Fatigue Property Map – Core Module** • Required for all fatigue analyses • User specifies one temperature between -40°C and 175°C • Fully relaxing (*R* = 0) conditions for all fatigue tests Deliverables Experiments • static tearing raw data • fatigue crack growth raw data (20 hour procedure) • monotonic tensile to failure 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-IS	**Elastomer Fatigue Property Map – Intrinsic Strength Module** • Recommended for cases with fatigue life longer than 10^6 cycles Deliverables Experiments • cutting force raw data, 3 strain levels Analysis and Reporting • cutting vs. tearing curve • intrinsic strength T_0 • fatigue threshold strain, stress, energy (if ordered with FPM-C)	$2,445
FPM-EL	**Elastomer Fatigue Property Map – Extended Life Module** • 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 curve • tearing energy T_c vs. ageing curve • 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

FPM-NR — **Elastomer Fatigue Property Map – Non-relaxing Module** — $3,000

- Recommended for cases where fatigue loading is never fully relieved to zero
- one temperature between -40°C and 150°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-TH — **Elastomer Fatigue Property Map –Thermal Extension Module** — $12,325

- Recommended for cases involving significant self-heating, thermal expansion, or thermal gradients
- User specifies three 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 3 temperatures • cyclic stress strain raw data at room temperature + 3 other temperatures • thermal conductivity, specific heat & density measurements • thermal expansion measurement	• heat generation law parameters describing dependence of hysteresis on strain and temperature • tear strength vs. temperature • fatigue crack growth rate law temperature sensitivity coefficient • coefficient of thermal expansion

FPM-CCG — **Elastomer Fatigue Property Map – Creep Crack Growth Module** — $1,615

- Recommended for cases involving long periods under static load
- User specifies one temperature between -40°C and 175°C

Deliverables

Experiments	Analysis and Reporting
• raw data from quasistatic creep crack growth procedure	• Creep crack growth rate curve and its parameters (T_q, r_q, and F_q)

FPM-S — **Elastomer Fatigue Property Map – Cyclic Softening Module** — $2,845

- Recommended for cases where stiffness degradation limits durability
- User specifies one temperature between -40°C and 175°C

Deliverables

Experiments	Analysis and Reporting
• raw data from cyclic softening procedure on simple tension strips at 5 strain levels	• Family of cyclic softening curves showing stiffness degradation rate as a function of life consumed • Curve fit to cyclic softening model

FPM-H23	**Elastomer Fatigue Property Map –Hyperelastic Module (23°C)** • Required as a prerequisite to Finite Element Analysis, lab ambient temperature 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 or ANSYS	$1,905
FPM-HX	**Elastomer Fatigue Property Map –Hyperelastic Module (-40°C<*T*<150°C)** • Required as a prerequisite to Finite Element Analysis • one temperature between -40°C and 150°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 or ANSYS	$2,585

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-C	Core Fatigue Testing	Test Temp: Test Freq:	5
	FPM-IS	Intrinsic Strength		3
	FPM-EL	Extended Life	Ageing Oven Temps (3):	30
	FPM-NR	Nonrelaxing		1
	FPM-TH	Thermal Extension	Test Temps (3):	6
	FPM-CCG	Creep Crack Growth	Test Temp:	1
	FPM-SFG	Cyclic Softening	Test Temp:	1
	FPM-H23	Hyperelastic (23 °C)	Peak strain levels:	4
	FPM-HX	Hyperelastic (other temperatures)	Peak strain levels: Test Temp:	4
			Total Slabs Sent	

Customer Notes:

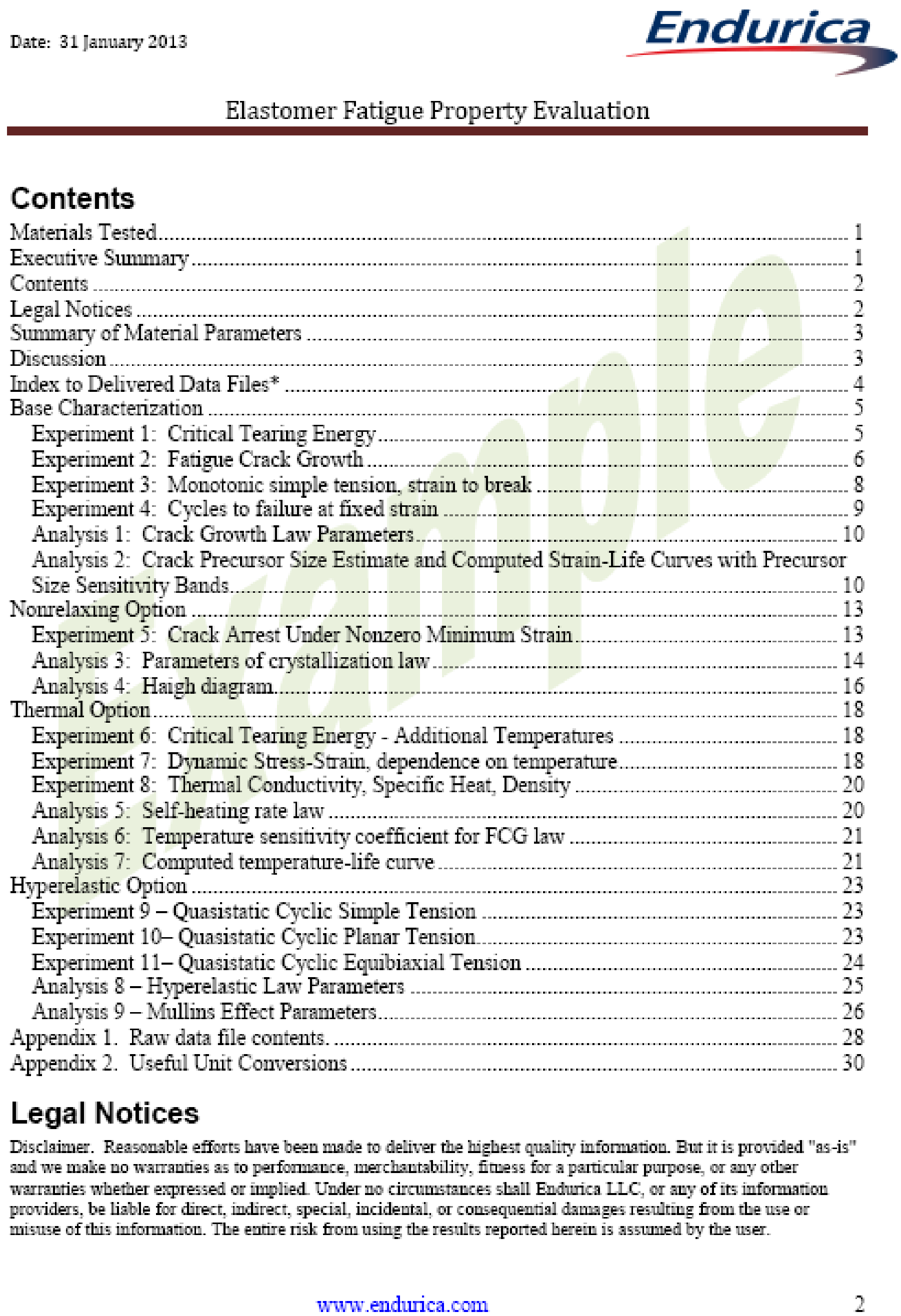
* Nominal slab dimensions are 150 mm x 150 mm x 2 mm.

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

3) Ship samples to:

Axel Products, Inc.
2255 S. Industrial Hwy.
Ann Arbor MI 48104
USA
Phone: +1-734-994-8308
Fax: +1-734-994-8309

Analysis and Summary Report Examples



Date: 31 January 2013

Endurica

Elastomer Fatigue Property Evaluation

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Figure 1. Example Table of Contents page for summary report.

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.

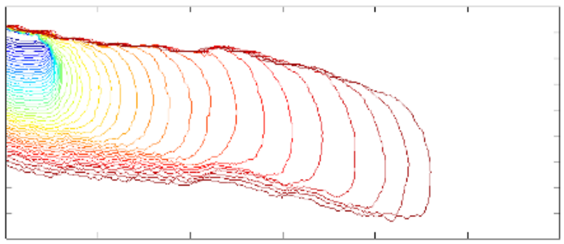

Figure 2. Typical crack tip images collected during fatigue testing. Each contour represents the crack tip shape at a given number of cycles. Colors indicate time, with blue at the beginning of the test, and deep red at the end.

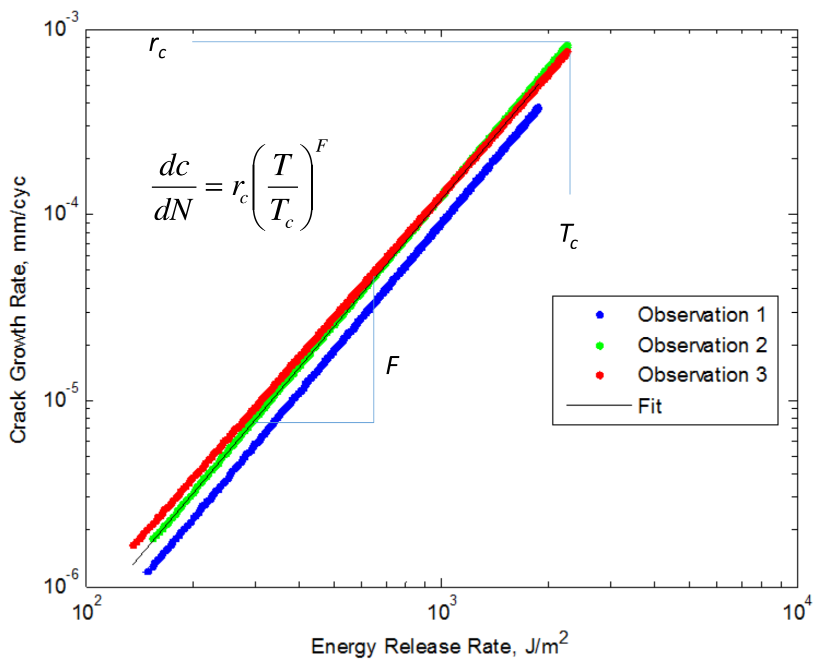

Figure 3. Fatigue crack growth rate observations and model fit parameters.

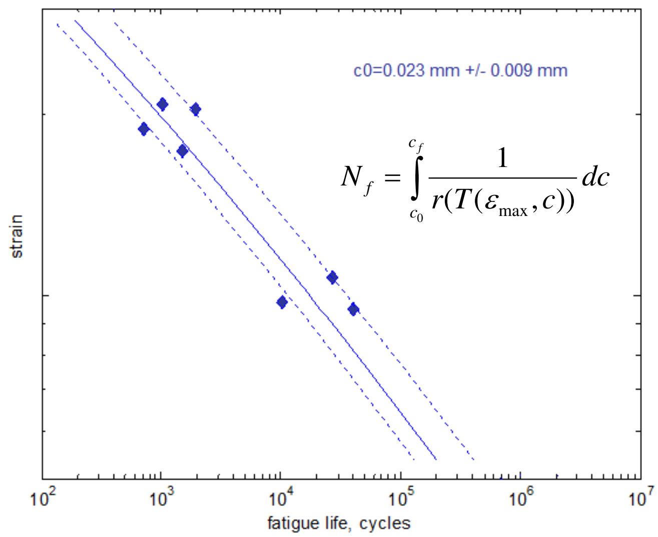

Figure 4. Crack nucleation experiments overlaid with computed strain-life curve corresponding to crack precursor size c_0. Dotted lines show the effect of crack precursor size variation on the strain-life curve.

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.

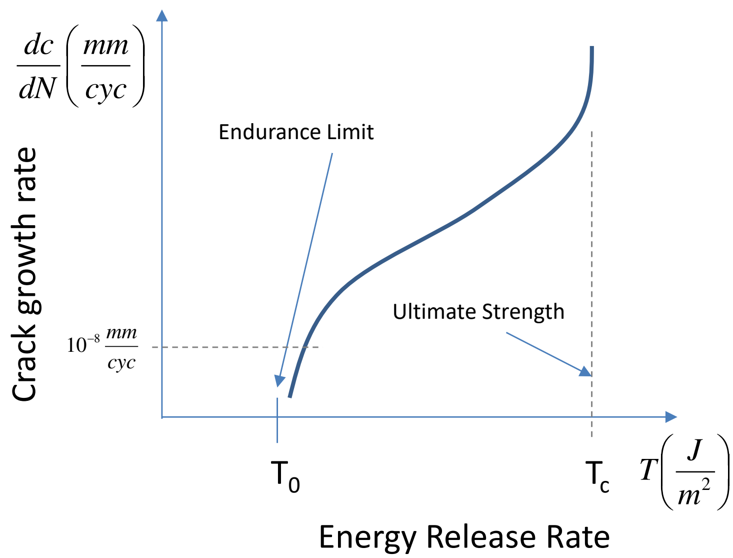

Figure 5. The fatigue endurance limit T_0 is the highest energy release rate that can be carried without incurring fatigue crack growth. Its value reflects the intrinsic strength of the polymer chains that must be broken in order to propagate a crack. It is measured via cutting experiments with a highly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

Fatigue Property Mapping – 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.

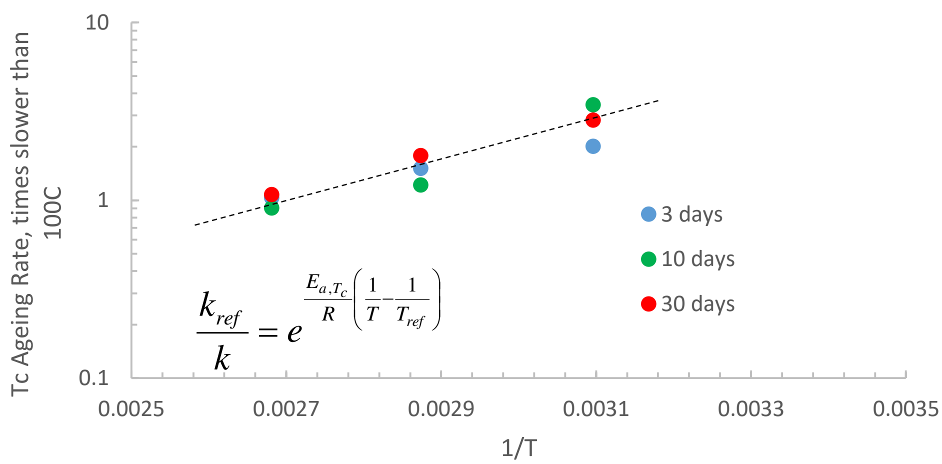

Figure 6. Determination of ageing rate dependence on time and temperature.

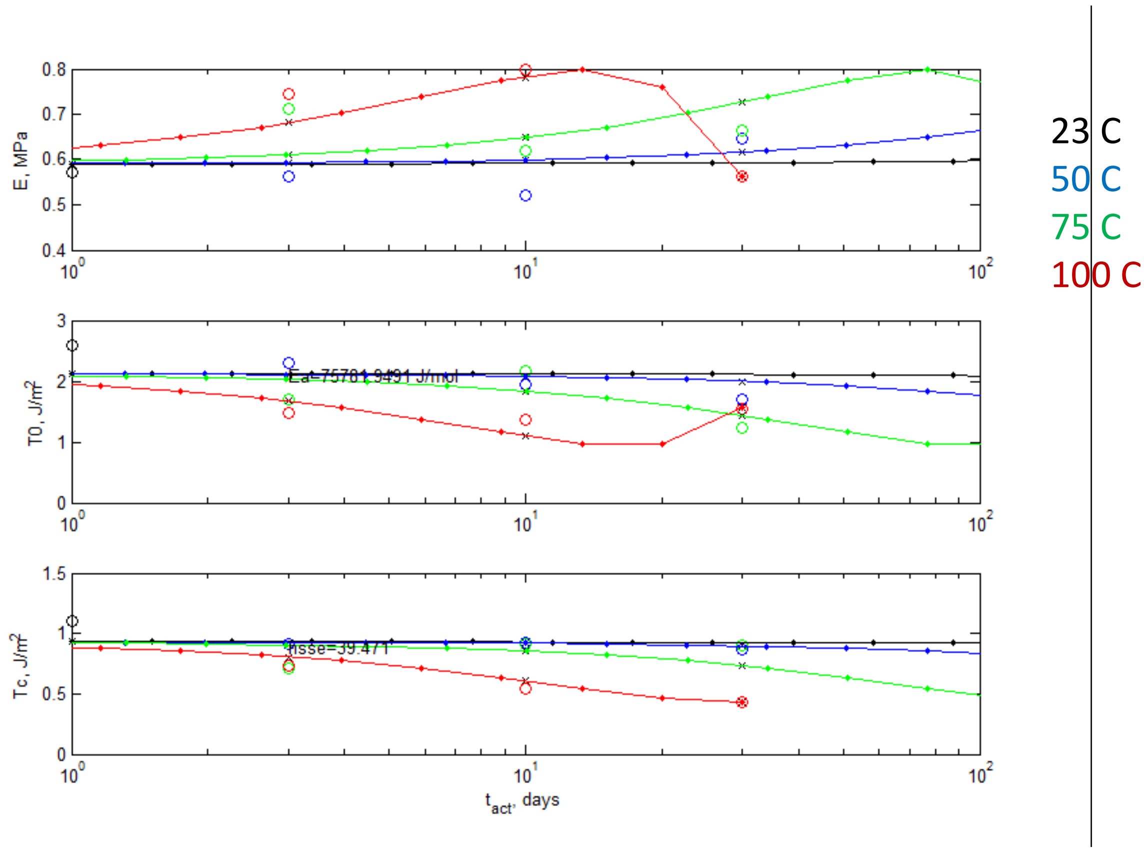

Figure 7. Ageing experiments over a 3x3 matrix of oven temperature and time settings are used to develop accelerated degradation curves.

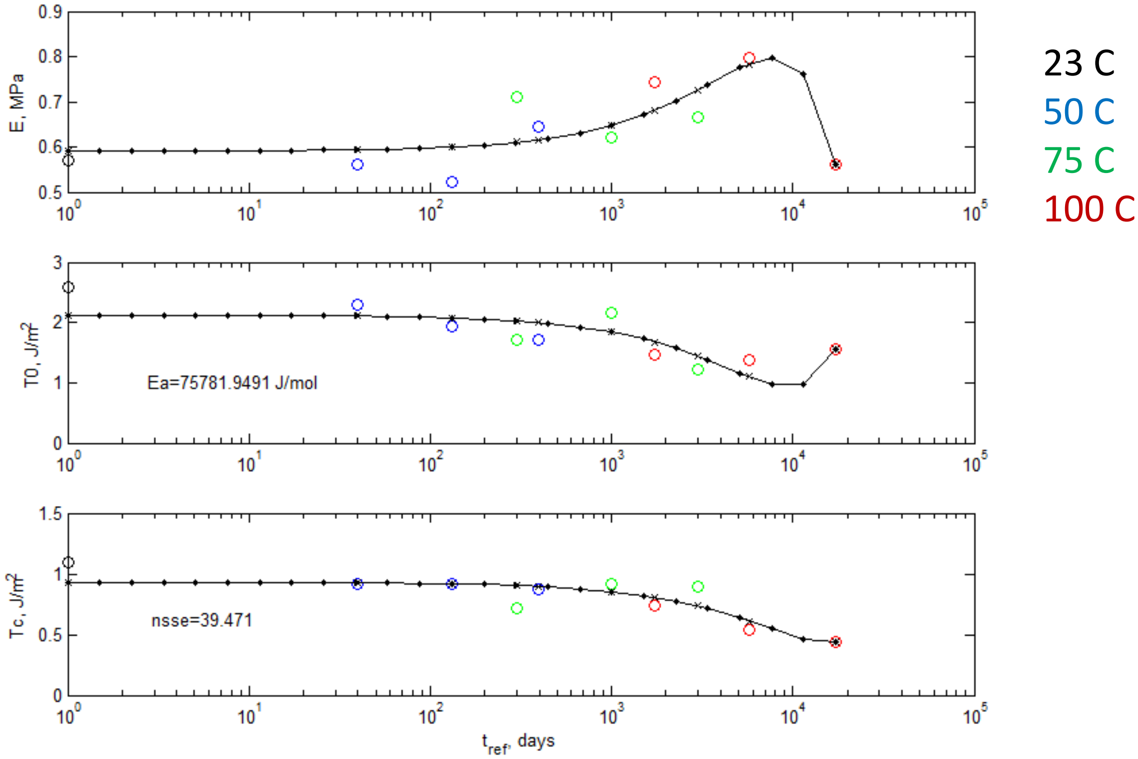

Figure 8. Based on the Arrhenius rate law, the accelerated degradation curves are compiled into a master curve for a specific reference temperature (here, the reference temperature is 23 degC).

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

Under nonrelaxing loads, some elastomers exhibit a strong improvement of fatigue life / retardation of crack growth that is attributed to strain crystallization. The effect can be 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.

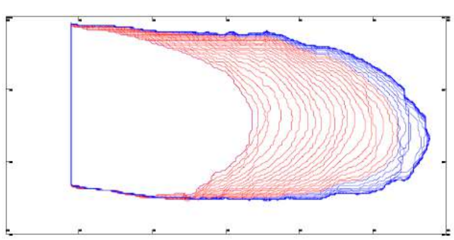

Figure 9. Crack tip images obtained during crack arrest experiments. Red images show the crack tip while growing under fully relaxing conditions. Blue images show the crack tip while growing under nonrelaxing conditions.

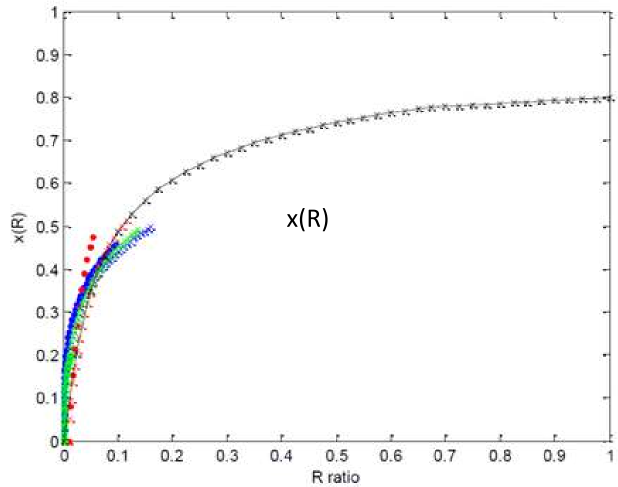

Figure 10. Typical strain-crystallization function *x*(*R*), showing dependence on the degree of nonrelaxation ratio *R* = Tmin / Tmax (where Tmin and Tmax are the energy release rate cycle extremes).

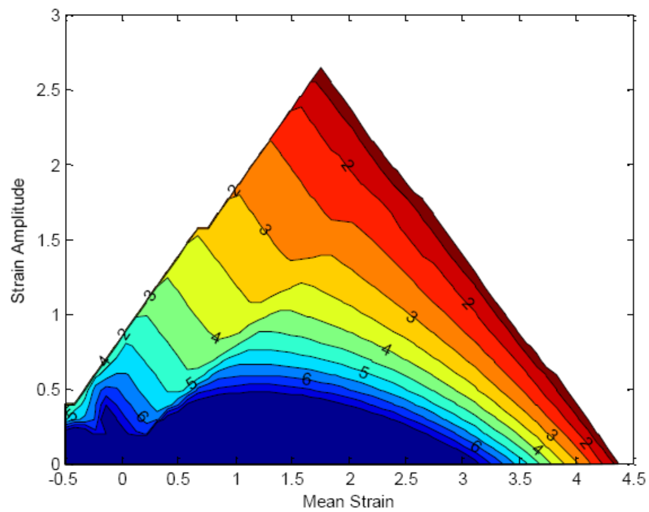

Figure 11. Typical Haigh diagram for simple tension/compression loading, computed based on crack growth measurements and crack precursor size inferred from nucleation experiments. Contours are colored and labeled according the the base 10 logarithm of the fatigue crack nucleation life.

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

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

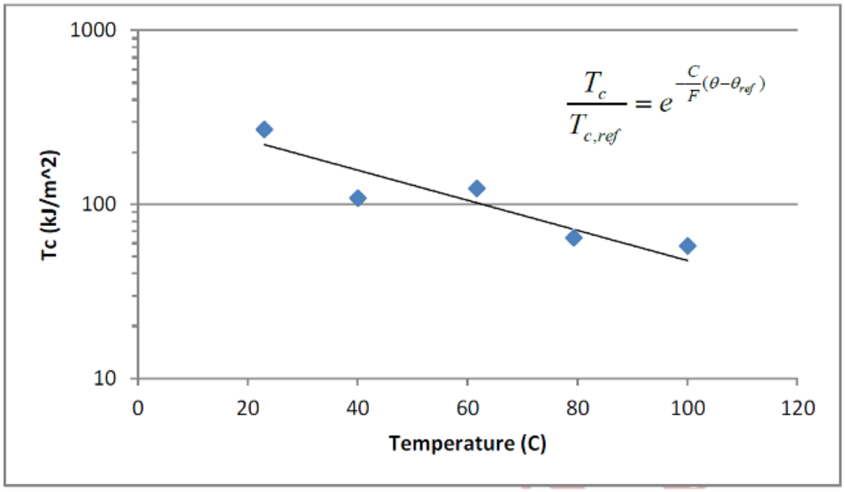

Figure 12. Dependence of tearing energy T_c on specimen temperature.

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.

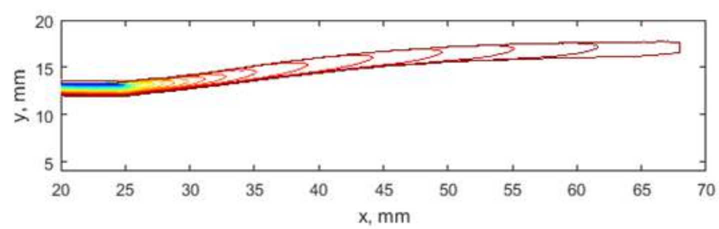

Figure 13. Typical crack tip images collected during fatigue testing. Each contour represents the crack tip shape at a given number of cycles. Colors indicate time, with blue at the beginning of the test, and deep red at the end.

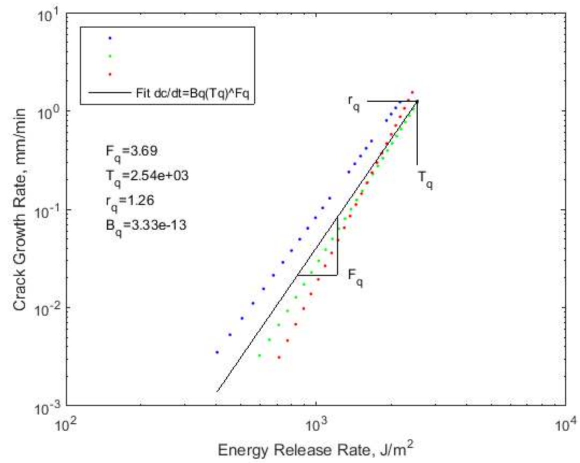

Figure 14. Fatigue crack growth rate observations and model fit parameters.

Fatigue Property Mapping – Hyperelastic Module Example Results (FPM-H23)

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.

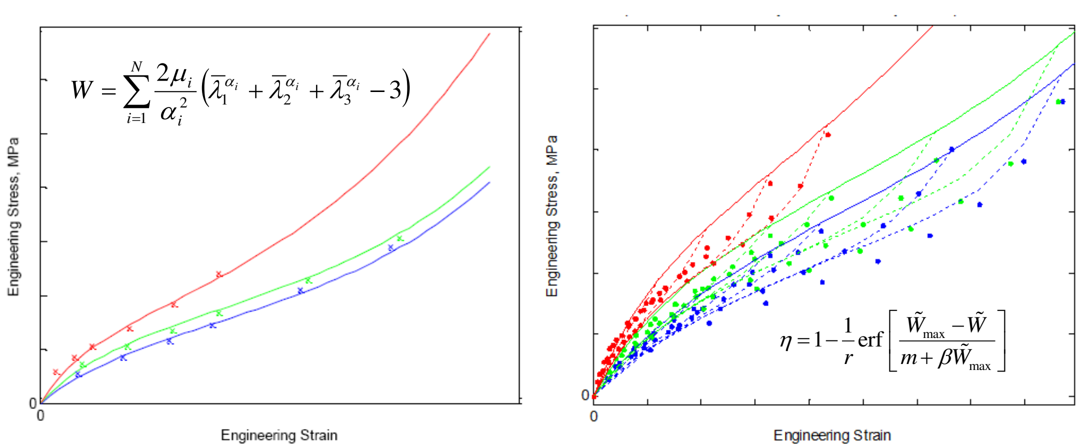

Figure 15. The lefthand plot shows typical hyperelastic law fit to stress-strain curves measured in simple (blue), planar (green) and equibiaxial (red) tension. Observations are shown with symbols, best fit with solid lines. The righthand plot shows typical Mullins law fit to cyclic stabilized stress-strain curves.

About This 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, see the website below for more information and schedule.

About Endurica LLC

Endurica LLC develops the world's most versatile and best-validated fatigue life simulation system for elastomers. Through its technology and services, Endurica empowers its customers to analyze 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. The company was founded in 2008.

www.endurica.com

About Axel Products

Axel Products provides testing services for engineers and analysts. The focus is 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, fe-safe/Rubber, MSC.Marc, ANSYS and LS-Dyna. Testing services are also provided to examine sealing and fatigue problems, long term thermal mechanical testing and high strain rate testing. The company was founded in 1994.

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