

Rubber fatigue ≠ metal fatigue: thermal effects

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All materials are temperature dependent, but some more than others: metals tend to be crystalline solids and will melt at sufficiently high temperatures; in contrast, crosslinked elastomers are always solids. They can be glassy or rubbery, crystalline or amorphous. When heated to extreme temperatures, they burn rather than melt, producing new substances, usually low molecular weight hydrocarbons (i.e. tarry substances and smoke). Of course, you do not have to melt or burn a material to see the effects of temperature. In fatigue analysis, we are concerned with stress-strain and crack growth behaviour. These can be temperature dependent for both metals and rubbers. However, while metals have a very high thermal conductivity, rubbers have almost the lowest. Therefore, fatigue analyses involving large temperature gradients are much more common in rubber than in metal.

As shown in Fig.1, while a 100°C temperature gradient in a metal can affect the fatigue tensile strength or the fatigue limit by 10% [1], the same 100°C temperature gradient in rubber can reduce the fatigue life by four orders of magnitude [2]!

Temperature and segmental mobility

The mechanisms underlying the elasticity of metals and rubbers could hardly be more different. Under stress, atoms in a metal's





crystal lattice are displaced from their equilibrium positions, and potential energy is stored in strained interatomic bonds. In rubber, however, the strain energy is not predominantly stored in strained atomic bonds. Rather, elasticity arises because the constituent long-chain molecules are much more likely to be randomly coiled than to be fully extended.

Thus, provided the molecules are sufficiently agitated by random thermal fluctuations, an entropic spring effect is created, meaning that potential energy can be stored by working to reduce the entropy of the polymer chain network by increasing the end-to-end distance of individual polymer chains [3].

Polymers in general can exhibit both glassy and rubbery behaviour, depending on the temperature. The rubbery state — in which entropic elasticity dominates — exists above the glass transition temperature T_g if the molecular motion rate is sufficiently high. In the rubbery state, very large strains are possible and the rubbery elastic storage modulus E'_r determines the stress-strain curve.

Below $T_{g'}$, however, the lack of thermal molecular mobility prevents molecular reconfiguration, resulting in a glassy stiffness



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 E'_{g} that is several orders of magnitude higher than E'_{r} . Polymers operating below T_{g} are thus not capable of large elastic strains and instead exhibit inelastic behaviour when strains exceed a few percent. Fig.2 shows how the storage and loss moduli vary through the glass transition (left), and how the molecular motion rate depends on temperature (right). The relative rate $\varphi(T)/\varphi(T_{g})$ of molecular motion as a function of temperature T is described by the WLF equation [4], which has material constants A and B.

$$\ln\left(\frac{\varphi(T)}{\varphi(T_g)}\right) = \frac{A(T - T_g)}{B + T - T_g}$$

Since the fracture mechanical properties of rubber depend on the viscoelastic dissipation in the crack tip process zone, with higher dissipation associated with lower crack growth rates, frequency and temperature effects can be inferred accordingly. Viscoelastic master curves, such as those shown in Fig.2, can be used as part of the material property rate dependence specification in the Endurica solver.

Self-heating and thermal runaway

During a charge cycle, work W_L is done on the charge stroke, some of which W_U is recovered on the discharge stroke, as shown in Fig.3. The unrecovered part of the work H remains in the material as heat energy, increasing the temperature.

The rate of viscoelastic heating of rubber depends on strain amplitude, cycle rate (i.e. frequency) and temperature. The strain amplitude dependence of the viscoelastic storage and loss modulii, G' and G'' respectively, can be specified using the Kraus model [5, 6]:



Fig.2. Top: Rubber's elastic and viscous responses depend on temperature relative to the glass transition temperature $T_{g'}$: Bottom: The rate of molecular motion depends on temperature relative to the glass transition temperature Tg.



Fig.3. Work input W_L on the loading stroke is partially recovered as W_U on the unloading stroke. A portion H of the energy remains in the material as heat.

$$G'(\varepsilon_a) = G'_{\infty} + \frac{G'_0 - G'_{\infty}}{1 + \left(\frac{\varepsilon_a}{\varepsilon_{a,c}}\right)^{2m}}$$
$$G''(\varepsilon_a) = G''_{\infty} + \frac{2(G''_{max} - G''_{\infty})\left(\frac{\varepsilon_a}{\varepsilon_{a,c}}\right)^m + \Delta G''_U}{\left(\frac{\varepsilon_a}{\varepsilon_{a,c}}\right)^{2m} + 1}$$

where ε_a is the strain amplitude, and where G'_{ω} , G'_{0} , $\varepsilon_{a,c}$, m, G''_{ω} , $G''_{max'}$ and $\Delta G''_{u}$ are material parameters. The viscoelastic heat rate per unit volume can be calculated from:

$\dot{q} = H\omega = \pi\omega G''(\varepsilon_a)\varepsilon_a^2$

Due to the low thermal conductivity of rubber, small amounts of viscoelastic self-heating can produce large temperature gradients. Accurately accounting for thermal effects on rubber durability generally requires both a structural finite element analysis to calculate the stress and strain fields, and a thermal finite element analysis to calculate the temperature field. Endurica fatigue solvers can provide heat rate calculations in a coupled finite element simulation for both transient and steady-state thermal analyses.

In cases where the temperature in the rubber exceeds a critical value T_x , an additional heat rate contribution q_x occurs due to exothermic chemical reactions. The effect is illustrated in Fig.4, for a rubber cylinder subjected to a rotating bending load [7]. The thermal runaway starts after about 250 seconds. Both experimental (dashed line) and Endurica calculated (solid line) simulation results are plotted for the cylinder centre line (blue) and for the cylinder outer surface (green).



Fig.4. When temperature exceeds a critical value T_{x} exothermic chemical reactions can produce a thermal runaway failure. Plot (right) shows Endurica calculated transient temperature history (solid lines) for a rotating bending cylinder (structural finite element model shown on left). For comparison, experimentally measured temperature histories are also shown (dashed lines).



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The thermal runaway event typically results in rapid decomposition of the rubber into hydrocarbon gases (i.e. smoke/burning rubber) and low molecular weight substances (tar).

Reversible temperature effects

The crack growth properties of rubber reversibly depend on temperature. Higher temperatures tend to reduce the tear strength T_c of rubber and increase the crack growth rate, as shown in Fig.5 [8]. At lower temperatures, the tear strength is increased and crack growth is retarded. Endurica's crack growth models can be specified with a temperature dependence via the temperature sensitivity coefficient (see Table 1) or via a table look-up function.

Fig.6 shows the fatigue life as a function of temperature calculated from the parameters in Table 1 [2]. Over a range of 100°C, natural rubber loses approximately a factor of two in fatigue life, and styrene butadiene rubbers loses four orders of magnitude!



Fig.5. Increasing temperature causes the crack growth rate to increase. Results are shown for natural rubber [8].

Some rubbers undergo strain crystallization, which is beneficial when operating under non-relaxing conditions. The crystallization effect is strongly temperature dependent and decreases with increasing temperature.

Fig. 7 shows the Haigh diagram calculated by Endurica for three different temperatures: 23, 90 and 110°C. For example, at a mean

| | Natural Rubber | Styrene Butadiene Rubber |
|--|----------------------|--------------------------|
| Shear Modulus <i>G, MPa</i> | 0.26 | 0.26 |
| Precursor crack size $c_{o'} mm$ | 0.025 | 0.055 |
| End of life crack size $c_{\ell} mm$ | 1.0 | 1.0 |
| Reference temperature $\theta_{o'}$ °C | 20 | 20 |
| Temperature sensitivity coefficient, 1/°C | 0.0061 | 0.110 |
| Tear strength T_c , kJ/m^2 | 10.0 | 2.5 |
| Intrinsic Strength $T_{0'} kJ/m^2$ | 0.04 | 0.06 |
| Crack growth rate r_c at $T_{c'}$ mm/cyc | 5 x 10 ⁻³ | 50 x 10 ⁻³ |
| Thomas law slope F | 2 | 4 |
| Strain crystallization | Yes | No |

Table 1. Crack growth properties and temperature sensitivity for natural rubber (NR) and styrene butadiene rubber (SBR), estimated from measurements reported in [2].



Fig.7. Endurica calculated Haigh diagrams for natural rubber at 23, 90 and 110°C. Increasing temperature tends to reduce strain crystallization, with the result that the mean strain benefit associated with strain crystallization is reduced or even eliminated at high temperatures.



Fig.6. Endurica calculated dependence of fatigue life on temperature for natural rubber (Δ) and for styrene butadiene rubber (•), [2]. Compare to Fig.1.

strain of 100% and strain amplitude of 20%, the fatigue life at 23°C exceeds 10^6 cycles, but at 110°C the fatigue life is approximately 10^3 cycles. This effect has been confirmed experimentally in recent work by [9].

Irreversible temperature effects/ageing

Prolonged exposure to high temperatures can cause permanent changes in the crosslink density and mechanical properties of rubber, including stiffness and crack growth properties. The effect depends on the availability of oxygen [10], as shown in Fig.8.

When aged under Type I aerobic conditions, rubber becomes brittle as its strain at break λ_b decreases while its stiffness M_{100} increases. When aged under Type II anaerobic conditions, rubber tends to soften while its strain at break decreases.

The rate at which thermochemical ageing of rubber progresses can be specified in Endurica using the Arrhenius law [11] and its activation energy parameter E_a . When following a temperature history $\theta(t)$, Endurica integrates the Arrhenius law to determine an equivalent exposure time τ at the reference temperature θ_0 . *R* is the real gas constant.

$$\tau = \int_0^t e^{\frac{E_a}{R} \left(\frac{1}{\theta(t)} - \frac{1}{\theta_0}\right)} dt$$

The equivalent exposure time controls the evolution of the stiffness and crack growth properties with thermal history. As shown in Fig.9, the evolution of the crack growth





Fig.8. The evolution of rubber's properties during ageing depends on the availability of oxygen, and on the temperature [10]. Under aerobic conditions, ageing tends to increase stiffness while strain at break decreases. Under anaerobic conditions, ageing tends to decrease stiffness while strain at break decreases.



Fig.9. The crack growth rate law evolves as a function of the equivalent exposure time τ . Crack growth property evolution is specified in Endurica by the dependence of the rubber's tear strength $T_c(\tau)$ and its fatigue limit $T_o(\tau)$ on exposure time.

rate law is specified by a tabular function that gives the stiffness $E(\tau)$, the tensile strength $T_c(\tau)$ and the fatigue limit $T_0(\tau)$. The material properties are then updated iteratively according to the co-simulation workflow shown in Fig.10. This allows the effects of thermal history and ageing on fatigue performance to be considered.

Conclusion

There are many ways in which metals and rubbers differ in their behaviour, and thermal behaviour is one of the most important.

Rubber more often requires careful attention to thermal effects due to its exceptionally low thermal conductivity, its entropyelasticity, its visco-elastic properties and tendency to self-heat under cyclic

loading, the sensitivity of crack growth properties and strain crystallization to temperature, oxidation and ageing.

 Endurica's fatigue solvers provide
material models and workflows that capture these thermal effects,
enabling accurate analysis and "right first

enabling accurate analysis and "right first time" engineering.



Fig.10. Endurica DT's co-simulation workflow updates the crack length c, exposure time τ , and stiffness E so that stress, strain, and temperature fields can be updated during solution.

About Endurica

Endurica provides software, materials characterization services, consulting, testing instruments and training to help companies meet rubber durability targets during product design. The company's solutions put engineers in control of rubber durability issues early in the development cycle, when the greatest opportunities exist to influence performance, and before investing in costly testing of prototypes. Endurica is the world's best-validated fatigue life simulation system for elastomers and its workflow gets rubber products to market faster. Endurica serves leading companies in many sectors including aerospace/defence, agriculture, automotive, chemicals, consumer products, education/research, energy, healthcare/medical devices, high tech, industrial manufacturing, infrastructure, marine, raw materials suppliers, silicone suppliers, rail, and tyres. It provides rubber fatigue analysis tools that are accurate, complete and scalable. Visit endurica.com

References

[1] P. G. Forrest, *Fatigue of Metals*, Pergamon Press: Oxford, New York, 1962.

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- [2] G. J. Lake and P. B. Lindley, "Cut growth and fatigue of rubbers. II. Experiments on a noncrystallizing rubber", *Journal of Applied Polymer Science*, vol. 8 (2), pp. 707–721, 1964.
- [3] W. V. Mars and T. G. Ebbott, "A Review of Thermal Effects on Elastomer Durability" in Advances in Understanding Thermal Effects in Rubber: Experiments, Modelling, and Practical Relevance, G. Heinrich, R. Kipscholl, J. B. Le Cam and R. Stoček (eds.), pp. 251–324, Springer Nature: Switzerland, 2024.
- [4] M. L. Williams, R. F. Landel and J. D. Ferry, "The Temperature Dependence of Relaxation Mechanisms in Amorphous Polymers and Other Glass-forming Liquids", *Journal of the American Chemical Society*, vol. 77 (14), pp. 3701–3707, 1955.
- [5] G. Kraus, "Mechanical Losses in Carbon Black Filled Rubbers", in: *Journal of Applied Polymer Science: Applied Polymer Symposium*, vol. 39, pp. 75–92, 1984.
- [6] J. D. Ulmer, "Strain Dependence of Dynamic Mechanical Properties of Carbon Black-Filled Rubber Compounds", *Rubber Chemistry and Technology*, vol. 69, pp. 15–47, 1996.
- [7] J. Vaněk, O. Peter et al, "2D Transient Thermal Analytical Solution of the Heat Build-Up in Cyclically Loaded Rubber Cylinder" in Advances in Understanding Thermal Effects in Rubber: Experiments, Modelling, and Practical Relevance, G. Heinrich, R. Kipscholl, J. B. Le Cam and R. Stoček (eds.), pp. 31–52, Springer Nature: Switzerland, 2023.
- [8] D. G. Young, "Fatigue Crack Propagation in Elastomer Compounds: Effects of Strain Rate, Temperature, Strain Level, and Oxidation", *Rubber Chemistry and Technology*, vol. 59 (5), pp. 809–825, 1986.
- [9] B. Ruellan, J. B. Le Cam et al, "Fatigue of natural rubber under different temperatures", *International Journal of Fatigue*, vol. 124, pp. 544–557, 2019.
- [10] A. Ahagon, M. Kida and H. Kaidou, "Aging of Tire Parts during Service. I. Types of Aging in Heavy-Duty Tires", *Rubber Chemistry and Technology*, vol. 63 (5), pp. 683–697, 1990.
- [11] S. Arrhenius, "Über die Reaktionsgeschwindigkeit bei der Inversion von Rohrzucker durch Säuren", *Zeitschrift für Physikalische Chemie*, vol. 4 (1), pp. 226–248, 1889.

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