Thermo-Mechanical Fatigue

Increasingly, components across many industries are required to operate over a wider range of mechanical and thermal loads. These loads influence the overall durability and life of the component, and are often the main causes of failure. Accurate prediction of the failure location and the number of cycles to failure requires a method of capturing the response of the system to thermal and mechanical loads with high accuracy. This white paper highlights the ways that ANSYS' high-fidelity, seamless workflow can solve the inherently multiphysics problem of thermo-mechanical fatigue.

Why is Thermo-Mechanical Fatigue in Focus?

The push for lightweighting, increasing efficiency, decreasing emissions, increasing power density and enabling variable usage results in challenging duty cycles for components across the aviation, power, transportation and electronics industries.

More efficient ↑

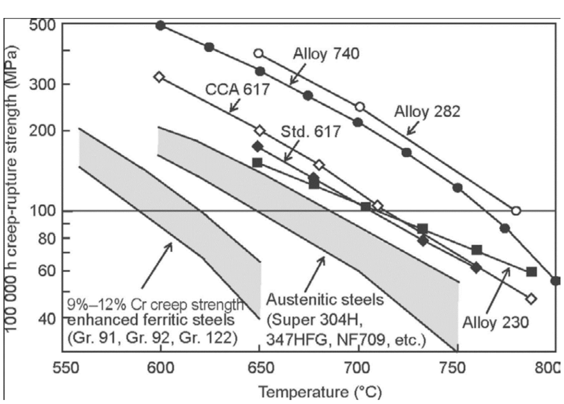
	Efficiency rate*	CO_2 intensity	Coal consumption	Steam temperature
Advanced ultra-supercritical	45–50%	670-740g CO_2/kWh	230-320g/kWh	700°c+
Ultra-supercritical	Up to 45%	740-800g CO_2/kWh	320-340g/kWh	600°c+
Supercritical	Up to 42%	800-880g CO_2/kWh	340-380g/kWh	Approx. 550°c-600°c
Subcritical	Up to 38%	≥880g CO_2/kWh	>380g/kWh	≤550°c

*Lower heating value

Source: Adapted from IEA, *Technology roadmap: High-efficiency, low-emissions coal-fired power generation*, 2012

Figure 1. Increase in steam temperature from subcritical to advanced ultra-supercritical

As an example, in the thermal power segment, advanced ultra-super critical power plants have been the recent focus of attention. These power plants are being designed to significantly increase efficiency while simultaneously reducing emissions to meet the new, aggressive standards. The standards require these plants to operate at a peak steam temperature of 760 C and pressures as high as 350 bar. Figure 1 illustrates how the peak steam temperature changes with advances in thermal power plant technology. These plants are also expected to operate with a load factor that can vary significantly due to the increased contribution of renewable energy to the grid. Conventional workhorse alloys of the power industry like ferritic alloys with Cr and Mo (e.g., P91/T91) cannot meet the design requirements of these conditions. More expensive heat-resistant nickel-based alloys are used in critical regions to meet the design requirements. Figure 2 illustrates how new heat-resistant alloys are needed to meet the creep characteristics needed for these power plants. The engineering challenge in designing components like boilers, turbines, valves and piping is to use the minimum amount of these expensive materials, while meeting all functional specifications of that component. Another challenge is to understand how these new materials behave at these operating conditions and under different usage scenarios, like different start-up and shut-down speeds, variability of loads, emergency situations and so on.



100,000-hour creep-rupture strength of some Ni-based super alloys, together with ferritic steels and austenitic steels, as a function of temperature (Abe, 2015)

Similar engineering challenges occur in the transportation industry, where components like in-cylinder, exhaust manifolds and turbochargers see high temperature and mechanical load variations that can lead to thermo-mechanical fatigue. For electronic components, the increasing power density of electronic packages, plus their increased usage in harsh environments, often causes thermo-mechanical fatigue.

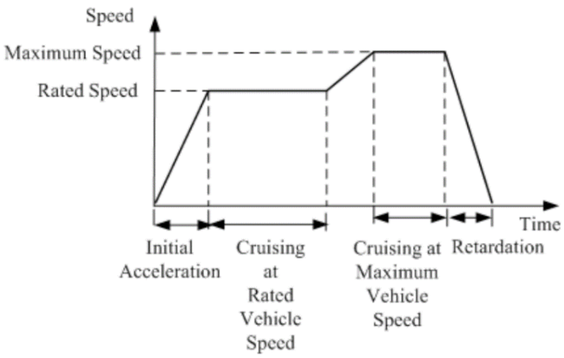


Figure 3. Representative duty cycle of an IC engine

MTS Landmark® test system configured for thermomechanical fatigue (TMF) testing

TMF test of round specimen, using induction heating, active air cooling and high-temperature extensometer

Figure 4. Typical type of TMF test rig

How Do Engineering Teams Design and Test for Thermo-Mechanical Fatigue?

Design and testing for thermo-mechanical fatigue can be broken into the following steps:

1. **Finalizing the Duty Cycle and Range of Operation**
   Understanding the number and types of duty cycles during which the component has to function as expected is important. These conditions dictate the types of mechanical and thermal loads the part will see in operation. In some cases, it is possible that the type of duty cycle might also be an output of the design process. For example, the start-up and shut-down sequence of a power plant might be governed by the lifing restrictions of thermo-mechanical fatigue, where lifing refers to the number cycles a component has left before failure.

2. **Selection of Materials**
   Selecting the right material for different parts of the component is critical in designing to minimize thermo-mechanical fatigue. Heat-resistant alloys are capable of functioning at the higher temperatures these components are subjected to. It is important to characterize how these alloys behave when exposed to different loads and conditions.

3. **Design for Function and Life**
   Engineers must design a component to achieve its desired function given the range of operation parameters and duty cycles involved. This will involve looking at different trade-offs, like strength versus weight and so on.

4. **Testing for Life**
   This would typically have involved physical testing using the "build and break" method to determine the life of the component. However, this method is extremely expensive, limiting an engineer to a handful of such tests in a design cycle. As a result, the component will be either hopelessly over-designed or a prime candidate for high warranty costs.

Simulation plays a crucial role in speeding up the design and testing of such components. Let's examine how that is achieved in detail.

It all starts with material characterization.

For material characterization, one would like to determine how the materials behave through physical testing of coupons under a variety of conditions:

1. Different temperatures. Generally testing is performed from room temperature to the highest operating temperature, but exploring higher temperatures is valuable to learn what might happen in a temperature runaway scenario.

2. Different strain ranges. Cycling over different strain ranges to failure indicates when plasticity starts, and the degree of work hardening versus kinematic hardening. It also helps to understand whether the material shows a non-masing hardening behavior, in which case the amount of hardening depends on the strain range to which the material has been previously exposed.

3. Different strain rates. Most metal alloys show significant rate behavior near and above half the homologous temperature (the absolute melting temperature of the alloy). So, for the relevant temperatures, the cycling of specimens is done at different strain rates — typically ranging from a cycle time period of a couple of seconds to several hundreds of seconds.

4. Different dwell periods. At high temperatures, these alloys show stress relaxation due to multiple mechanisms: easier movement of dislocations due to thermal activation, new grain formation and different creep mechanisms.

5. Different phases between thermal and mechanical strain: Metal alloys behave differently when the thermal and mechanical strain are in-phase(IP) versus out-of-phase (OP).

6. Different environments: How does the material behave in the presence or absence of oxygen. For example, determining the thermo-mechanical fatigue for a space component might require testing in an inert environment.

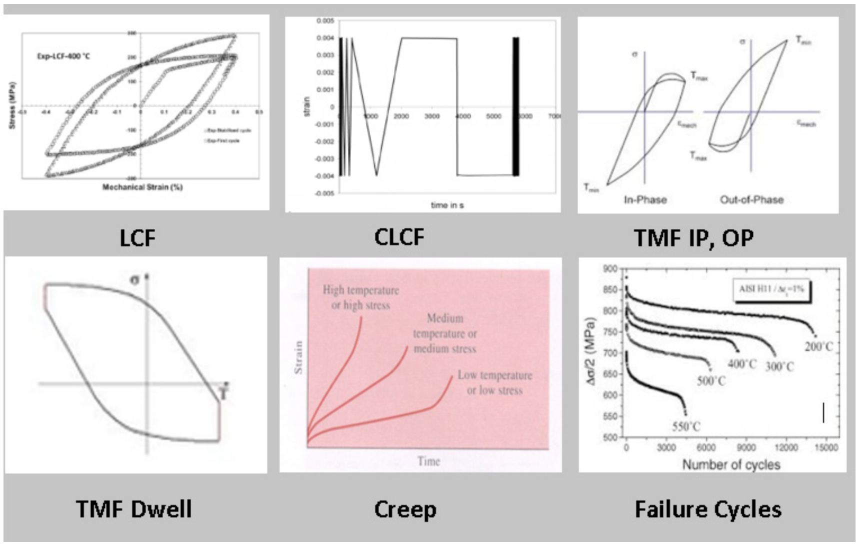


Figure 5. Typical tests and output curves to characterize materials for thermo-mechanical fatigue (TMF)

Physical testing typically takes a few months and results in 100+ tests in which the sample is tested to failure. This testing also helps in understanding the lifing characteristics of the material under different conditions.

All this is done by extensively testing coupons of the material on testing rigs where the variation of mechanical and thermal loads can be carefully controlled. Heating of the specimen is often done by electrical induction, and cooling by force convection of a fluid through hollow coupon specimens.

While physical test results give us a good understanding of how a small specimen of a material will behave under different conditions, they do not tell us how to design the component based on this information.

Hence the first important step in simulating thermo-mechanical fatigue is to ensure that the material behaves as predicted by the tests numerically. The nonlinear variation of stress and strain over space and time in the component determines the life of the component. It is therefore imperative that material characteristics are captured with high fidelity to be able to predict the true history of stress and strain throughout the component. ANSYS' state-of-the-art nonlinear material models help to capture these behaviors with high accuracy.

Unlike high cycle fatigue where the stress is often within elastic limits, low cycle fatigue is dominated by inelastic strains. Hence, it is important to capture these strains accurately, as they will determine the accuracy of the stress levels in the component. Accurate stresses and strains are prerequisites of most lifing models to predict low cycle life.

Inelastic strains essentially occur within grains as well as between grains of a polycrystal. Depending on the temperature seen by the material, these effects can be rate-dependent.

At temperatures lower than half the homologous temperature, the rate effects are not significant. In that case material behavior can be modeled using classical rate-independent plasticity theory. Cyclic testing of the alloy will reveal the extent of both isotropic hardening (work hardening) and kinematic hardening.

Isotropic hardening shows up more significantly at lower temperatures in the initial phase of cycling before stabilization as seen in Figure 6. The behavior is nonlinear and asymptotic over cycles.

ANSYS nonlinear isotropic modeling can effectively capture this behavior using the following formulation:

$$\sigma_Y = \sigma_0 + R_0\varepsilon_{pl} + R_\infty\left(1 - exp\left(-b\varepsilon_{pl}\right)\right)$$

Typically, in these applications the R0 value is taken at zero so that the work hardening asymptotes and the maximum peak stress that can be reached due to isotropic hardening alone is $\sigma_o + R_\infty$.

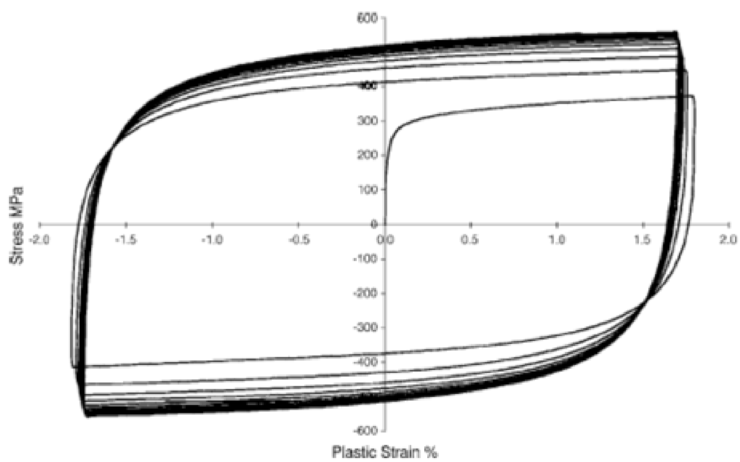


Figure 6. Typical isotropic hardening behavior seen with cycling

Kinematic hardening captures the Baushinger effect, in which the center of the yield surface moves in response to plastic strains; this center represents the back stress in the system. In these alloys this movement has a distinct nonlinear behavior and — similar to work hardening — has a limiting surface to which the yield surface can move. This nonlinear dependence of kinematic hardening on plastic strain (following the Armstrong-Fredrick law) is captured by incrementing the back stress with any additional plastic strain, and at the same time making it a function of the current back stress value which makes the curve nonlinear.

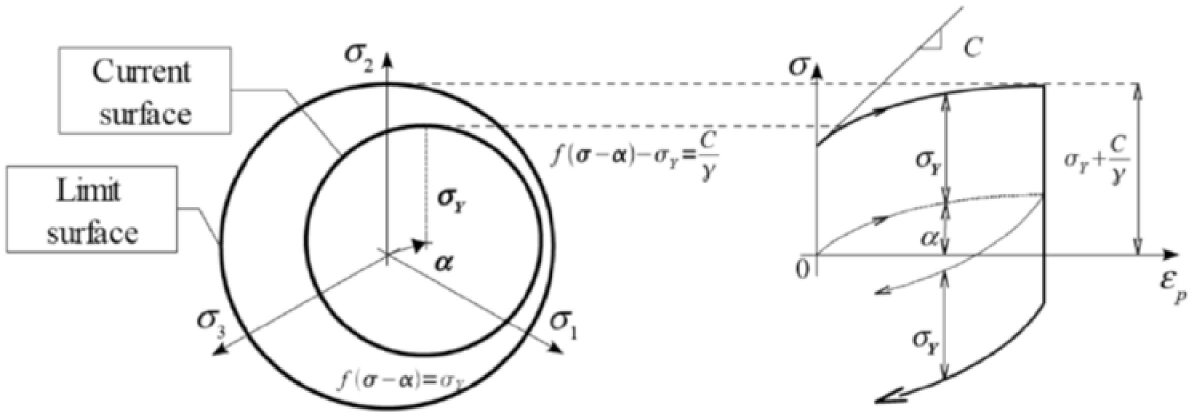


Figure 7. Nonlinear kinematic hardening using the Armstrong-Fredrick law

In the set of materials considered for this application, there are often three segments to this nonlinear back stress evolution curve. The first part is a rapid rise of back stress post-yield, followed by a smooth rounding of the curve akin to a bent knee followed by an almost linear portion that flattens gently with larger plastic strains.

ANSYS' implementation of the Chaboche model (which is essentially multiple layers of the Armstrong-Fredrick model) is able to capture these characteristics accurately. The formulation for the incremental of back stress is as follows.

$$d\alpha = \sum_{i=1}^{M} d\boldsymbol{\alpha}_i,\ d\boldsymbol{\alpha}_i = \frac{2}{3}C_i d\varepsilon_{pl} - \gamma_i \boldsymbol{\alpha}_i dp$$

As seen from this equation, the resulting back stress can be additively decomposed into multiple layers. Typically, three layers in the Chaboche model are considered to capture the nonlinear behavior explained earlier as seen in Figure 8. The first layer has a relatively high C1 and Y1 to capture the steep rise, followed by a lower C2 and Y2 to capture the rounding of the curve, followed by a C3 value that represents the final linear slope of the curve with a very nominal Y3 value to asymptote the final part of the curve at large plastic strains.

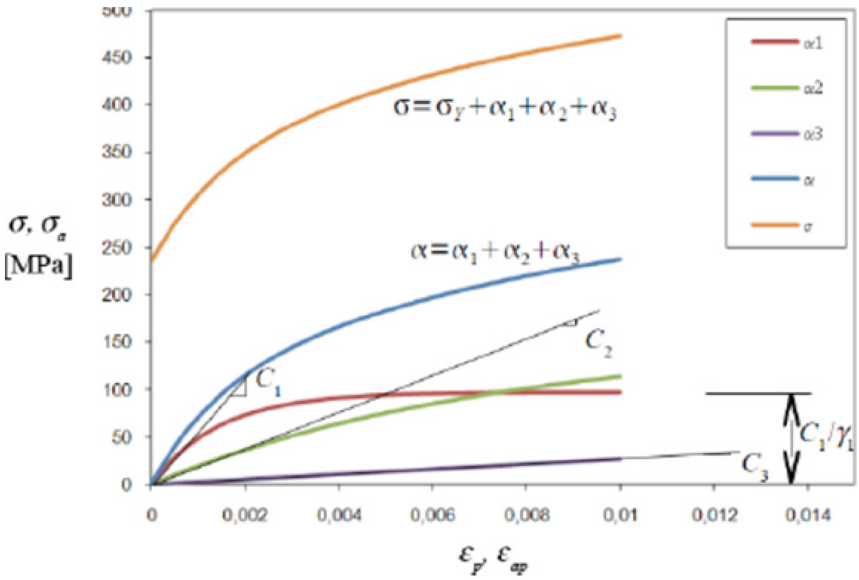


Figure 8. Additive decomposition of the back stress tensor in the Chaboche model

Chaboche parameters are often fitted based on strain-controlled cycling tests with zero mean stress, which prevents the effect of ratcheting to be seen. However, as the components go through a duty cycle, different points might cycle about different mean stress values, and severe buildup of plastic strains due to ratcheting might be seen locally. If the plan is to capture the buildup of plastic strains due to ratcheting by solving many duty cycles, then particular care needs to be given to the almost linear layer of the Chaboche model. For instance, in a three-layer Chaboche model the value of ϒ3 will determine whether one will see shakedown (seen with ϒ3 = 0) versus linear ratcheting (ϒ3 = a small positive value). The effect of the small differences in the almost linear layer ϒ values is not distinguishable in a strain-controlled cycling test. They need to be calibrated by doing ratcheting tests at different mean stresses or different stress ratios.

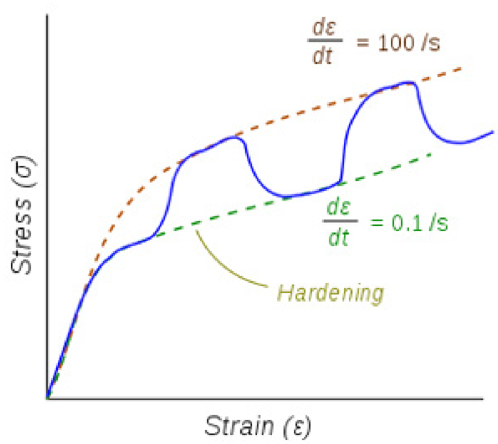


Figure 9. Viscoplastic effects as one moves between two strain rates

Rate effects start showing near and above half the homologous temperature. At these temperatures, thermal activation enables mechanisms like defects to move out of plane. However, the relative time scales of the rate the strain is applied causes dislocation pile-up, which can be avoided through thermal activation. This is captured through a viscoplastic model, which essentially follows what is known as the over-stress model. This model's characteristic is that at a very slow plastic strain rate it follows the rate-independent plasticity, and the stress is at the yield surface. However, at higher strain rates the stress can lie beyond the yield surface, but it will fall back on to the yield surface in an asymptotic fashion as the strain rate decreases. Also, depending on the level of stress, the rate of fall of stress for a strain rate can change significantly.

Figure 9 shows the effect of viscoplasticity as a material is loaded alternatively across two different strain rates. ANSYS' recommended viscoplastic model for TMF simulation is the EVH model, whose formulation is as follows:

$$\dot{\varepsilon}_{pl} = \sum_{i=1}^{n} \left(\frac{\sigma - \bar{\sigma}_0}{K_i} \right)^{1/m_i}$$

This EVH model has multiple layers that can capture the viscoplastic behavior at different stress levels.

Another rate effect seen at high temperature occurs when the back stress, which manifests as micro stresses at grain boundaries, gets diffused and released if kept at the high temperature for some time. This causes the center of the yield surface to drop back to its initial state over time. This drop is nonlinear and is a strong function of the back stress itself.

This rate effect is captured by enabling the static recovery term in the ANSYS' Chaboche model. The formulation of that terms is as follows:

$$\frac{C_i}{{M_i}^{m_i}}|\alpha_i|^{m_i-1}\alpha_i$$

To be able to determine the coefficients for the static recovery term, it is important to not only look at a good fit with respect to experimental data in the stress-strain space, but also to look at the stress-time space. For an Ni-based 230 alloy the stress relaxation at high temperatures (850 C) is shown in Figure 10. There are multiple effects that cause the stress relaxation (viscoplasticity, static recovery, low stress creep), so care should be taken while fitting the coefficients.

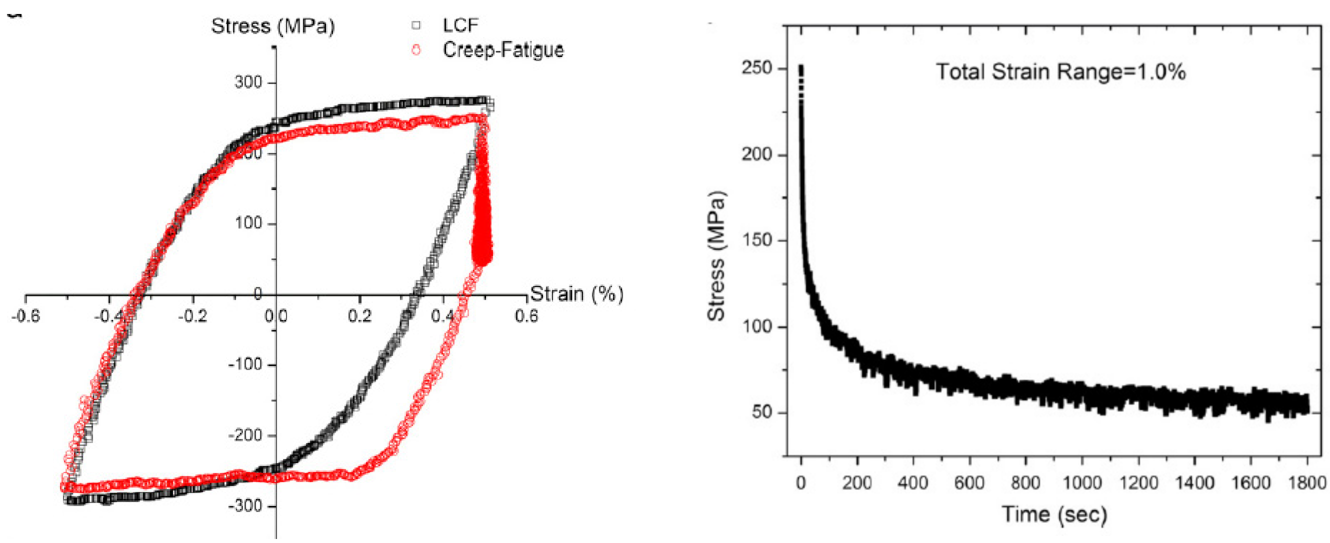


Figure 10. Stress drop in Ni-based alloy 230 at 850 C (Chen et al.)

During long dwell periods inelastic strains might be generated due to mechanisms like diffusional creep, where the stress level might be within the yield surface. In this case, ANSYS' creep model also needs to be activated.

ANSYS has several creep model formulations, and they are all compatible with the above stated model. As an example, ANSYS' Norton creep model is shown here:

$$\dot{\varepsilon}_{cr} = C_1 \sigma^{C_2} e^{-C_3/T}$$

The above set of models captures the mechanical behavior of the material seen when components experience varying thermal and mechanical loads.

As discussed previously, depending on several parameters (temperature, time scale, type of loading) some of the above models might dominate while some might not influence the material's behavior much.

Figure 11 is a snapshot showing how one could decide the combination of material models to characterize the material based on the simulation being carried out in ANSYS.

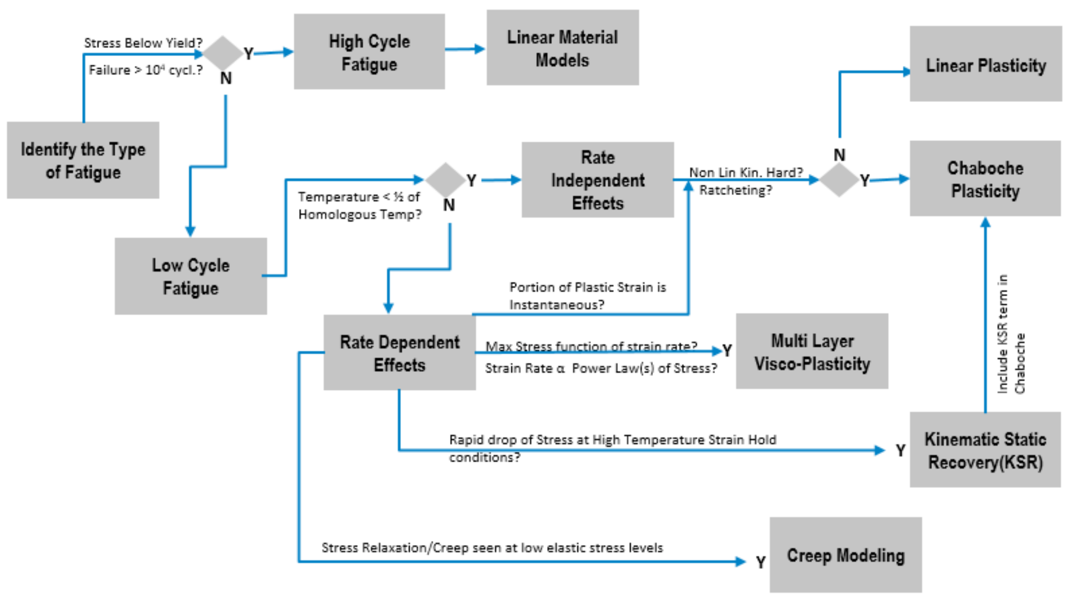


Figure 11. Material model combination decision-making tree for fatigue

Finding the coefficients of these material models for the 100+ set of test curves is a study in itself. Typically, one would create a virtual test setup of a single element using the above material models and look for the degree of fit with experimental data. This would be done typically by using insights shared earlier of which effects dominate in each type of test. One could also use ANSYS DesignXplorer optimizer to study potential sets of candidates.

Once the material is characterized, the next step is to study what the component experiences as it goes through the duty cycle. If we mimic reality in total, we would have to solve potentially for very long periods of time, which would not be practical. Alternatively, one could use accelerated testing techniques widespread in industry which would reduce this time significantly. However, that too would be computationally difficult. The practice in industry is to take a representative cycle approach. Essentially this means that can one examine the experience of the component through a duty cycle somewhere during its life (often taken at mid-life cycle) and look at the damage that happens in that cycle to calculate life. So, the lifing model is tuned such that the damage represented by this cycle matches the average damage seen per cycle. Also, the material characterization described is also with respect to how the material behaves at this duty cycle.

To mimic the conditions of this duty cycle, one would have to put this component through thermal and mechanical loads as it varies during the cycle. Essentially this is a multiphysics transient problem. It is imperative that we capture the thermal transients accurately, as that will determine the temperature gradients in the system, which in turn determine the thermal stresses in the system. On the structural side, capturing the inertia effects is not as important, and we are fine with capturing the stresses caused by a temperature gradient at a time point without the inertia effect. ANSYS enables you to solve for high-fidelity temperature distribution by considering all the mechanisms of heat flow. For instance, ANSYS CFD products enable you to study detailed conjugate heat transfer where all the fluid effects and thermal effects are considered. This includes, for instance, state-of-the-art models involving combustion, turbulence, multiphase, radiation and so on to capture all elements that could potentially influence the thermal solution. Alternatively, one can do a simpler thermal analysis in ANSYS Mechanical where we do not solve for the fluid flow but assume some heat transfer coefficients at the fluid interfaces (which can also be obtained from CFD simulations).

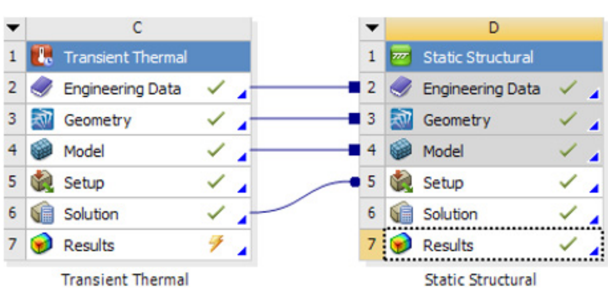
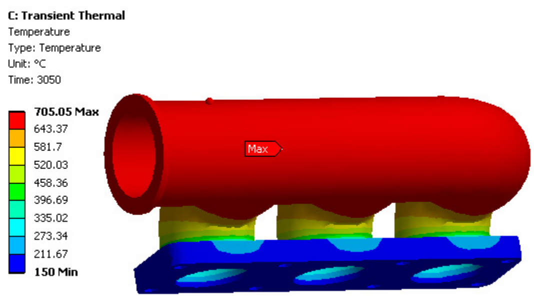


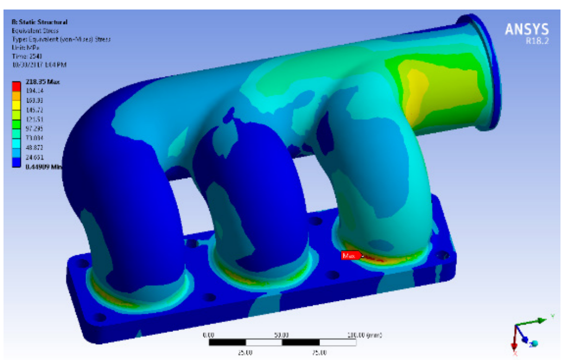
Figure 12. ANSYS WorkBench schematic for solving for thermo-mechanical fatigue

Typically, though we would like to capture just one cycle, we would do at least three cycles of this thermal analysis to get a periodic repeating thermal solution. These thermal solutions temperatures are mapped on static simulations as described before to get the nonlinear stress-strain variation for a duty cycle. While the inertia effects are not being considered in the structural simulation, one needs to keep in mind that the time associated with a sub-step has a meaning for the rate-dependent terms of the material modeling.

Figure 12 is a typical workflow that shows the three-duty-cycle thermal loading and workflow mapping.



Temperatures at a time point



Stresses at the same time point

Figure 13. Thermal and stress results for an exhaust manifold

The stress and strain that is developed in the third cycle as seen in Figure 12 is used for calculating the local damage that is happening in the component. One can then calculate the limiting life for the components and the limiting locations. Different industries and customers follow different lifing calculations that capture the crack initiation, and in some cases also try to capture the predicted crack propagation.

ANSYS' high accuracy and streamlined solutions for thermo-mechanical fatigue are used across industry segments to develop innovative designs using new materials under harsh conditions in less time.

About the Author

Prem Andrade is a Senior Engineering Manager at ANSYS, Inc. He has over 20+ years of experience working with customers from all industries using ANSYS to solve their engineering problems. His current areas of interest include durability and lifing, and he has been working with many customers in the area of thermo-mechanical fatigue.

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