Predicting 3-D Fatigue Cracks without a Crystal Ball

ANSYS tools quickly predict 3-D thermomechanical fatigue cracking in turbocharger components.

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Honeywell Turbo Technologies produces nearly 9 million turbochargers annually for the automotive industry. Because turbochargers undergo wide thermal swings, they are subject to thermomechanical fatigue cracking.

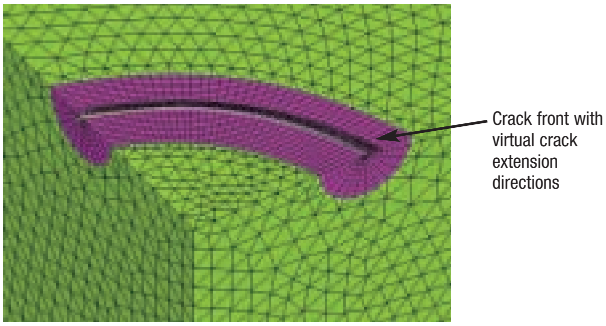
Turbochargers increase the power and boost the fuel efficiency of internal combustion engines, but engineering teams find they pose unique design challenges. For example, because the turbine is driven by the engine's own hot exhaust gases, components must withstand widely varying thermal stresses as temperatures cycle between 120 and 1,050 degrees Celsius for engine speed variations relating to idle, acceleration and braking.

In particular, components such as the cast-iron housing that directs hot gases into the turbine are subject to thermomechanical fatigue cracking — a problem that often is not discovered until parts fail in qualification tests. To replicate four to five years of severe thermal shock loading — far greater than parts would experience in normal operation — engineers perform rounds of tests that each can be very expensive and take weeks to complete. Several of these rounds generally must be performed before arriving at a workable design that passes scrutiny. Many stress intensity factor formulas are available in handbooks for predicting fatigue crack growth with simplified 2-D geometries; typically, though, these formulas are not applicable for complex part geometries under elastic–plastic conditions in high-temperature environments with multi-axial loading. As a result, many part designs are based on modifying previous geometries, trial-and-error testing cycles and, in many cases, "crystal ball" best-guess predictions based partly on conjecture and simplified assumptions.

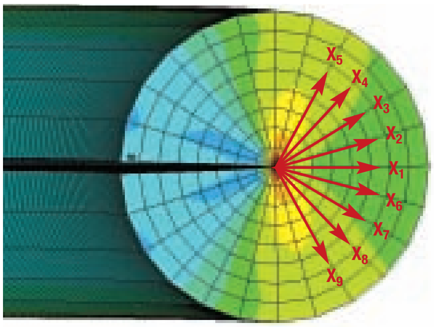
Honeywell Turbo Technologies overcomes these limitations by using ANSYS Mechanical software together with the ANSYS Parametric Design Language (APDL) scripting tool to calculate the probability of a crack initiating as well as its most likely growth rate, length and 3-D path. Predicting crack fractures in this manner at the early stages of component development enables engineers to optimize designs upfront and help avoid qualification test failures. Conversely, the analysis gives engineers information on the presence of small benign cracks that do not lead to loss of component functionality (for example, gas leakage or turbine wheel rub) and can, therefore, be ignored.

For this application, J-integral analysis capabilities in ANSYS 12.0 provide a robust solution to predict crack behavior at high temperatures. The J-integral is a path-independent fracture mechanics parameter that calculates energy release rate and intensity of deformation at the crack front for linear and nonlinear material behaviors. The J-integral approach generally works best with hexahedral meshes for the highest possible accuracy. But representing the entire structure with a hex mesh is a tremendous drain on computational resources. So in this case, Honeywell Turbo engineers used two separate meshing techniques: hexahedral elements for representing the instantaneous crack front (a cylindrical volume around the crack front called the crack tube) and tetrahedral elements for the remaining part volume.

Connectivity between the two different mesh patterns is assured with ANSYS transition elements. The size of



Hexahedral elements represent the expected path of 3-D crack propagation (called the crack tube), and less-complex tetrahedral elements are used for the remaining volume of the part.



The 3-D crack growth direction determining the propagation path is based on a virtual extension direction angle in which maximum energy is released.

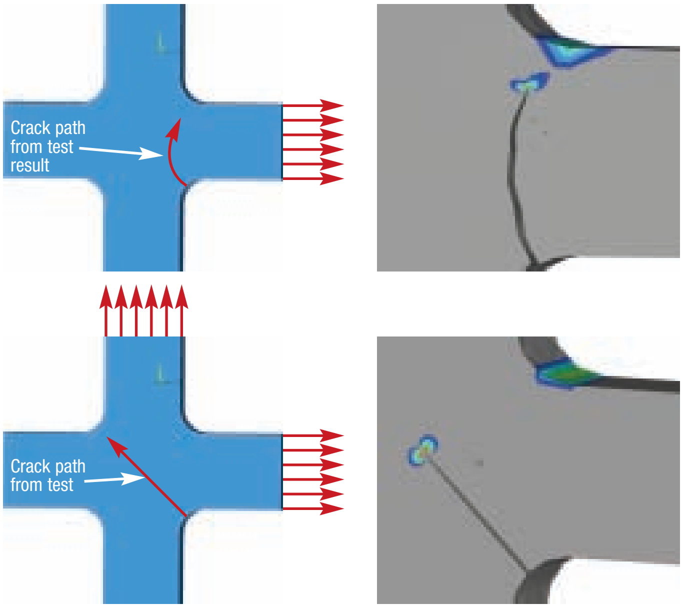
the 3-D crack tube depends on the volume of the crack path's plastic zone and is based on the number of rings of elements and the number of contours to be used in calculating J-integral values using the ANSYS `CINT` command. The number of element rings and contours should be high enough to maintain path independence and accuracy of energy release rate.

In this way, ANSYS software calculates J-integral values at each increment of crack propagation along several user-defined virtual crack extension directions. The crack feature is updated in a third-party CAD code at each increment, then imported into ANSYS Mechanical software where it is meshed, solved and post-processed. The cycle continues until a target criterion is reached. All processes are integrated and controlled using in-house APDL scripts. By leveraging improved fracture mechanics capabilities in ANSYS 12.0 for calculating J-integrals, the method provides a new approach to model and simulate arbitrary 3-D crack growth and to compute mixed mode stress intensity factors along the crack front within the simulation software.

This method requires calculations to be performed iteratively for thousands of crack-growth cycles — a prohibitively labor-intensive and time-consuming task if performed manually but one well-suited to the automation capabilities of the APDL scripting tool. Along with techniques such as submodeling and load blocks for more efficient solution processing, such automation radically increases the speed of performing these iterative calculations.

Honeywell Turbo analyzed a test case using this method to predict growth behavior of paths in a cruciform specimen under uniaxial and biaxial loading. The uniaxial load case shows prominent crack turning while the biaxial case shows near planar growth. The results obtained validate the approach. The team completed further runs to validate crack growth rates that show promising results.

Using this automated ANSYS fatigue crack prediction process has the potential to increase engineering productivity significantly, with crack growth analysis time reduced by more than 90 percent compared to manual methods. This speedup has significant value, since Honeywell Turbo engineers must analyze as many as 400 designs annually, and demands will likely increase in the coming years as turbochargers are implemented on a growing number of vehicle models around the world. In this way, technology from ANSYS is playing a critical role in enabling the turbocharger company to strengthen its leadership position in this competitive industry sector. ■



Crack path directions in cruciform specimens under uniaxial loading (top) and biaxial loading (bottom)