Validation of Virtual Life Management®
with Aluminum 7075 Test Data
for Smooth and Bolt Hole Specimens
under Spectral Loading

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ABSTRACT

VEXTEC's fatigue simulation capability predicts the fatigue life of components based on the microstructural material properties of the alloy rather than using large empirical datasets. Current industry standard methods determine fatigue life based on time consuming and expensive physical component testing. VEXTEC's component fatigue model is unique because it uses intrinsic material properties and very limited testing to accurately predict fatigue durability.

The model simulates the microstructure of the material using probabilistic material properties such as grain size, grain boundary stress intensity factor, Poisson's ratio, particle size and particle density. The simulation then predicts the number of cycles to complete each stage of fatigue damage: crack nucleation, short crack growth and long crack growth.

In a validation case, the fatigue model was created for a common aircraft alloy, aluminum 7075-T651, using material properties and a limited set of smooth bar fatigue test points. This same fatigue model accurately predicted the fatigue life for a flat plate in bending and a 2-hole specimen in complex mission. Physical fatigue testing validated the fatigue predictions.

VEXTEC can use this algorithm to model the fatigue durability of aircraft components. Accurate health management algorithms for component fatigue can be developed through modeling rather than extensive and expensive testing. PHM systems will benefit from a widely applicable model that accurately predicts structural reliability.

INTRODUCTION

This paper discusses a probabilistic micromechanics model which provides accurate fatigue life predictions of aircraft structures by taking into account the material's unique features from micro to macro-scale. This fatigue model helps in determining the frequency of inspections as it has the potential to offer the most accurate predictions of life expectancy variations, i.e. the risk of failure at any time, instead of only predicting average lives. The model is used to reduce the rising costs of replacing aging structures with newer ones.

Most current fatigue models used by industry are empirical in nature. The material's microstructural features are either completely ignored while predicting the fatigue lives or accounted for through phenomenological quantities such as scaling parameters. Therefore, the design analysis must rely on past experience with similar designs, field failure data and costly tests of actual components. The limitations of the current approach cause conservative (heavier than required) designs in some cases and optimistic (less durable than desired) designs in others.

Traditional fatigue prediction methods can create accurate models for a single component and load state after testing and careful inspection for crack nucleation and propagation. The model presented here can predict crack nucleation and propagation by modeling the microstructure from intrinsic material properties. Since this algorithm models the fatigue crack growth at the microstructure level, there are many advantages. Complex and variable missions can be modeled explicitly as cycle-by-cycle stress can be applied to the microstructure. Geometry becomes an extrinsic input to the model; therefore fatigue life can be predicted for any geometric configuration. Initial flaws and defects can be explicitly modeled on the grain structure.

Fatigue response is highly sensitive to a material's microstructure. Therefore, fatigue analysis methods must have a microstructural basis. It is also recognized that the microstructure is highly stochastic in nature. Thus, a probabilistic basis must be incorporated into the fatigue analysis process. Field failure problems are generally driven by one or more conditions leading to much earlier failures than traditional design approaches predict. Such conditions include but are not limited to extreme-value conditions on locations and sizes of accumulated damage generally associated with fatigue. The resistance of damage-tolerant design concepts to various damage states must be known in terms of the extreme value conditions (the tail of the curve) in order to prevent premature field failures. The presented approach taken to this problem is a combination of traditional processing and life characterization with new, advanced technologies related to probabilistic design and structural analysis methods.

For many structural applications, most of the fatigue life is spent in the nucleation and small crack growth regimes.

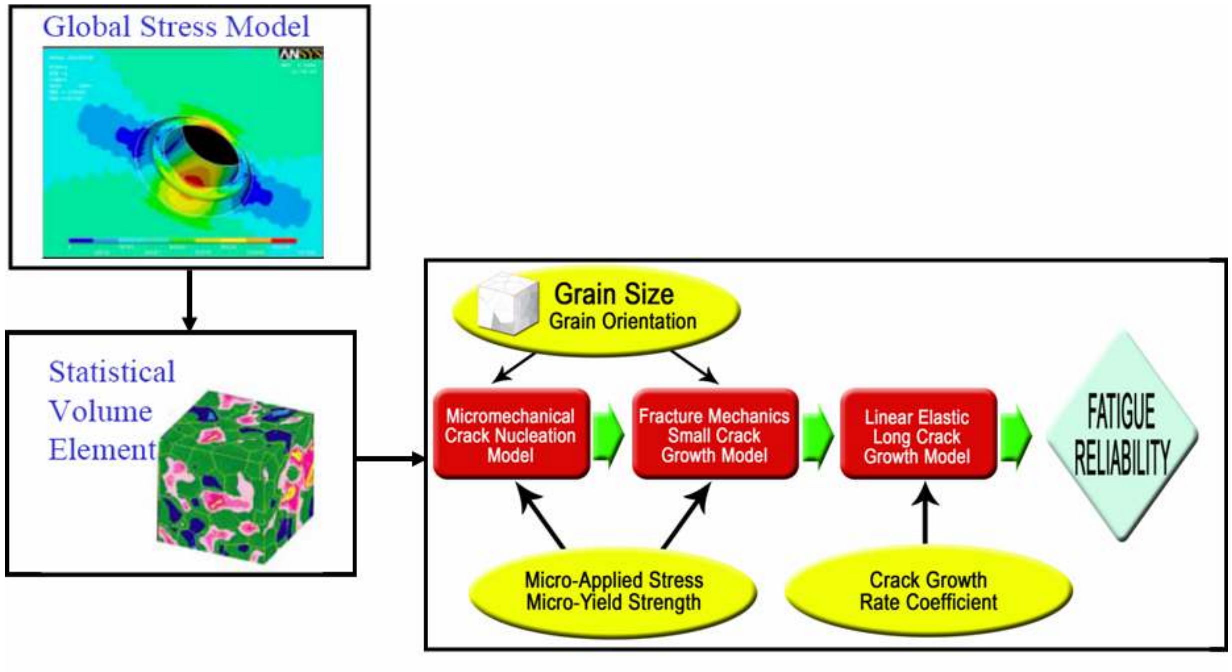


Figure 1: Elements of the probabilistic micromechanics model algorithm.

The modeling and simulation of this early crack behavior is vitally important in fatigue prediction, yet is typically not considered by fracture mechanics methods. The presented methodology takes into specific account these regimes by modeling the grain size, grain orientation, particle size and population, micro-applied stress and micro-yield strength along with other microstructural parameters. Crack nucleation and small crack growth models incorporate this randomness using Monte Carlo probabilistic techniques. For long crack growth simulation, randomness is incorporated by allowing the crack growth rate properties to vary. A computer simulation was used with built-in material libraries in which appropriate modeling linkages are established to predict the scatter in fatigue life. [1, 2, 3]

FATIGUE DAMAGE MODELS FOR ALUMINUM

Through numerous DoD funded efforts over the past several years, VEXTEC has developed a probabilistic fatigue life prediction algorithm that explicitly models fatigue crack initiation and growth at the microstructural level. The algorithm has been extended to prognosticate the fatigue characteristics of aluminum structures.

The probabilistic micromechanics model predicts the variation in fatigue life based on statistical variation of the material microstructural features. The model provides the underlying information concerning the failure mechanism involving crack nucleation life, short crack life and variations in the total fatigue lives that are vital for analyzing how a design will perform in the field.

In all regimes, damage is simulated cycle-by-cycle to determine cycles to failure probability of the microstructure. As a load greater than the crystallographic yield strength is applied to a grain with diameter d, dislocations are generated and move along the slip plane. The dislocations pile up at the grain boundary and particles, acting as obstacles to dislocation movement. The dislocation movement is assumed to be irreversible such that when the reverse load is applied, dislocations in the opposite direction stack up on a closely spaced plane. Since the residual load from the back stress of the positive dislocations act in the same direction as the reverse applied load, unloading will cause negative dislocation movement. During each of the subsequent load cycles, the number of dislocations monotonically increases.

Experimental evidence of 7075-T651 indicated that for the load experienced by the components, cracks nucleated at second phase particles of a size on the order of the particle.[4] These cracks nucleated very early in life, in some cases on the first cycle. Therefore the model was developed under the assumption that a population of initial cracks existed identical in size and density to the second phase particles. These cracks grew (or arrested) as small cracks.

Small cracks are important when considering in-service conditions for structural applications. A critical crack in a highly loaded, high-strength component may be as small as a surface crack less than 0.5 mm (0.02 in.) in length. Typical crack growth studies consider large (greater than 5 mm) cracks. The effect of microstructure is recognized as fundamental to the small crack growth stage. Small cracks are strongly influenced by individual microstructural features. Although the microstructure has been shown to influence large crack growth behavior, this effect involves the mass rather than individual grains.

A simple linear dependence of small crack growth rate on crack tip opening displacement (CTOD) has been observed for many alloys:[5]

$$\frac{da}{dN} = C'\Delta\phi_t \qquad (1)$$

where a is the crack size, N is the number of cycles, C' is an experimentally determined coefficient, and ϕ_t is the CTOD. The CTOD is predicted based on the interaction of the crack tip plastic zone with the microstructure.

The CTOD model is based on the theory of continuously distributed dislocations.[6] Consider a crack with the crack tip in the j^{th} grain and the slip band tip in the n^{th} grain as shown in Figure 2.

If the slip band is propagating (not blocked by the grain boundary), the size of the slip band zone can be found from:

$$\begin{aligned}\phi_t = {} & \frac{2k_j a}{\pi^2 A}\ln\frac{c}{a} \\ & +\sum_{i=j+1}^{n}\frac{(\tau_{i-1}-k_{i-1})-(\tau_i-k_i)}{\pi^2 A}g(a;c,L_{i-1}) \\ g(a;c,L_{i-1}) = {} & L\ln\left|\frac{\sqrt{c^2-L^2}+\sqrt{c^2-a^2}}{\sqrt{c^2-L^2}-\sqrt{c^2-a^2}}\right| \\ & -a\ln\left|\frac{a\sqrt{c^2-L^2}+L\sqrt{c^2-a^2}}{a\sqrt{c^2-L^2}-L\sqrt{c^2-a^2}}\right|\end{aligned} \qquad (2)$$

where t_i is the applied resolved shear stress in the i^{th} grain, k_i is the frictional stress of the i^{th} grain, a is the crack length, c is the crack plus slip band length, L_i is the distance from the free surface to the grain boundary of the i^{th} grain preceding the slip band tip, and $g(a;c,L_{i-1})$ is a relative size parameter. Eq. is for a freely propagating slip band tip. For a slip band tip blocked by microstructural obstacles, Eq. is modified.[6] The CTOD from Eq. is used in Eq. (1) to determine the small crack growth rate.

The last phase of damage accumulation is the long crack growth phase. The long crack growth rate is modeled using linear elastic (or elastic plastic) fracture mechanics. The microstructural variations are not explicitly considered. All variation in long crack growth is modeled by allowing the fracture mechanics coefficients to be random variables.

The total cycles to failure are determined by adding the number of cycles spent in each stage of damage accumulation.

FATIGUE ACCUMULATION ALGORITHM

A component experiencing fatigue is modeled as an ensemble of individual grains and particles. Each grain is modeled as a single crystal with a unique combination of properties generated using the Monte Carlo technique. Likewise each particle is modeled as an initial small surface crack. The material properties are derived partially from metallurgical analysis of the aluminum material. The microstructure of the aluminum material is shown in Figure 3.[7] Each of the three planes of the material has different size grains and particles which contribute to dramatically different fatigue properties. From this metallurgical analysis, we derive some of the material properties distributions found in Table 1. (The distribution parameters are not shown in the Table.)

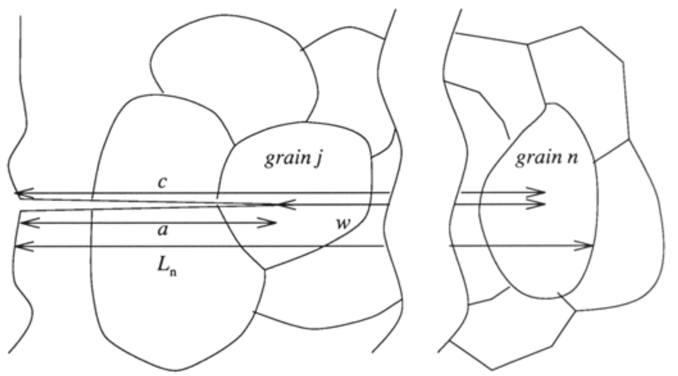


Figure 2: Crack tip slip band in multiple grains.

Using this input, the fatigue algorithm uses the following steps:

Step 1. The simulation starts by "generating" a surface crack of a specimen equal in size to the particle.

Step 2. The microstructure in which the small crack will grow is created by populating zones in front of the nucleating crack. The zone is filled with randomly sized grains. Random properties include size, orientation, frictional strength, and the locally applied stress. All other properties are considered deterministic parameters. Because the grain size is random, the number of grains in each zone is random. Additional zones are generated until the average properties of the grains within a zone are equal to the bulk properties.

Step 3. The small crack growth model of Eq. (1) is used to determine the number of cycles needed to grow the crack through the zones. The crack size at the end of the small crack phase is equal to the largest zone size.

Step 4. The large crack growth model is used to determine the number of cycles in the long crack growth phase. The crack fails based on a crack size criterion.

Step 5. The number of cycles for the two phases is summed. This is the life of a crack that is initiated from this surface particle.

Step 6. Steps 1 through 5 are repeated for another surface particle of the specimen. This process is continued for each surface particle which exceeds a crack growth criteria for very small cracks. The generation of the

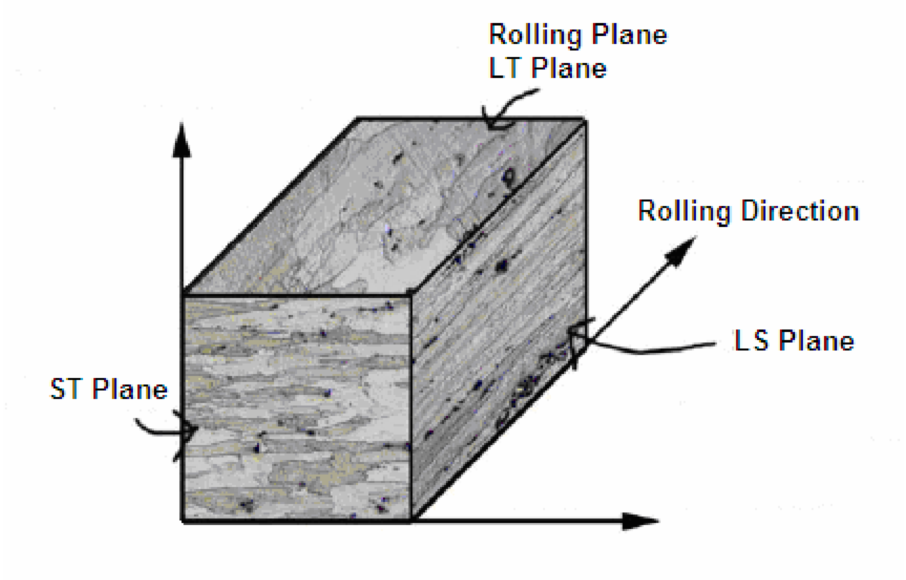


Figure 3: Al7075-T651 microstructure. [7]

specimen has been completed when the total number of the surface particles is equal to the population density for the surface area of the specimen. The life of the specimen is set equal to the minimum life of any surface particle.

Another specimen is generated and virtually tested by repeating steps 1 through 6.

Table 1. Typical parameter distribution for the model.

Variable	Description	Distribution
C'	CTOD Law Coefficient	Deterministic
d	Slip length	Lognormal
G	Bulk shear modulus	Deterministic
k	frictional strength	Weibull
K_C	Grain boundary SIF	Deterministic
C	Paris Law Coefficient	Lognormal
n	Paris law exponent	Deterministic
W_S	Specific fracture energy	Deterministic
σ	Micro-stress	Normal
v	Poisson's ratio	Deterministic
A	Gage section area	Deterministic
d_S	Defect size	Lognormal
d_d	Defect density	Lognormal

If the fatigue analysis of a component using finite element method (FEM) is being performed, steps 1 through 6 are performed for each element of the FEM. The generation of the element would be completed when the total number of the surface particles is equal to the population density for the surface area of the element. The life of the element is set equal to the minimum life of any surface grain.

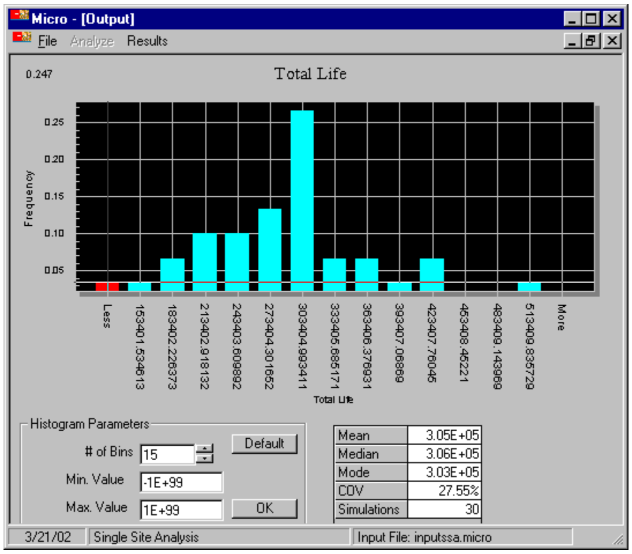
Another element is generated and virtually tested by repeating steps 1 through 6. When all of the elements have been simulated, the fatigue life of the component is set equal to the minimum life of any element. Another component is generated and virtually tested by repeating the process.

A software program was written to perform the above algorithm. The program has four major units. Of these four units, the first three represent the three consecutive stages of crack growth: (a) nucleation, (b) short crack growth, and (c) long crack growth. The fourth unit is the reliability computation module. Nucleation is included for completeness, although the nucleation life is assumed to be zero for this alloy and loading condition.

The analysis engine uses Monte Carlo techniques to simulate many globally identical components. Each component has a unique microstructure and thus a unique fatigue response. Reliability computations are performed on the ensemble of simulated components to determine statistical descriptions such as average, variation, and distribution type.

The output graphical user interface (GUI) of the results from the microstructural fatigue software presents several post-processing options. Figure 4 shows the probability density function (PDF) of the total life of the component. In addition to the PDF plot, the statistical parameters of total life (Mean, Median, Mode and COV) are tabulated on the right hand bottom corner of the window. The number of simulations performed is also displayed below the table.

The output also presents a statistical analysis of the parameter state at the critical location that caused failure of the component (i.e., the critical particle size is the size of the grain that initiated failure). The non-failed cracks are the number of cracks that did not contribute to failure but existed when the component failed. The same information available from laboratory test or field inspections is generated by the simulation.



Histogram Parameters

of Bins: 15

Min. Value: -1E+99

Max. Value: 1E+99

Mean	3.05E+05
Median	3.06E+05
Mode	3.03E+05
COV	27.55%
Simulations	30

3/21/02 Single Site Analysis Input File: inputssa.micro

Figure 4. Probability density function (PDF) for the total life of a component.

APPLICATION AND DEMONSTRATION OF REAL PART AND REAL LOADING

The probabilistic micromechanics model combined with a crack coalescence module was used to predict the fatigue lives of aluminum 2-hole specimens subjected to a loading spectrum representing an aircraft. The test was performed for the DARPA SIPS program.[8] A sample of one of the two missions is shown in Figure 5. These missions include multiple high and low excursions and random R-ratios.

The microstructural fatigue model was developed with smooth bar test results. As discussed in previous sections, the microstructural fatigue model is based on the intrinsic material properties. The geometry and stress are extrinsic parameters. Once the microstructure model is developed for the material, any geometry and stress can be used. The model was developed with only smooth bar test values at a single stress value and R-ratio = –1.0. This same microstructure fatigue model was used to predicted the fatigue life of the 2-hole specimen for the spectrum loading. These predictions and test results are shown in Figure 6.

Fatigue life analysis was performed to simulate the experimental conditions and local damage mechanisms of a 2-hole specimen. The specimens were subjected to the loading spectrums at room temperature. Fatigue cracks initiated as surface cracks at second phase particles and the nominal crack propagated along a plane which is perpendicular to the loading direction. The specimen is considered to be failed when the crack is completely through the material. Figure 6 shows the comparison of model results for 10 specimens (red dots) with the OEM test data (blue triangles) for the 2 hole specimen as well. This model shows excellent correlation with the test results for both spectrums.

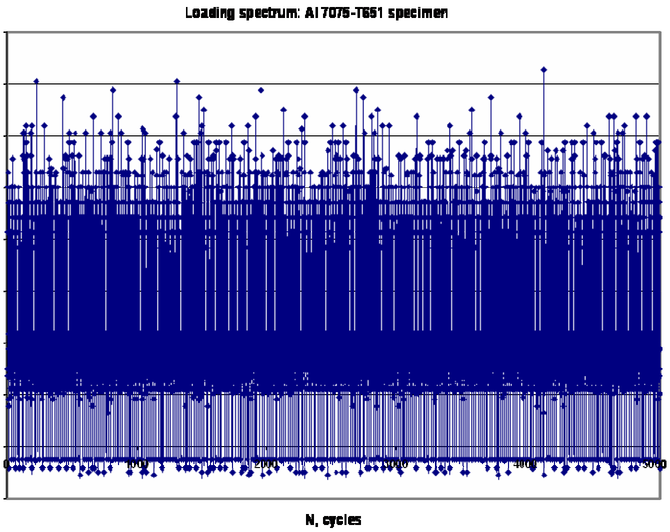


Figure 5: Sample mission loading spectrum used in the fatigue prediction.

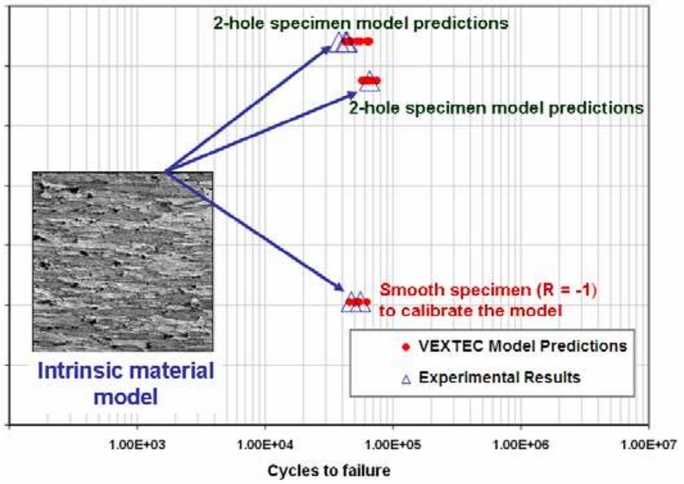


Figure 6: Simulation results for two different loading spectrums: Probabilistic micromechanics model results proved to be an excellent match with the experimental data provided under DARPA SIPS [4, 8]

VEXTEC also conducted another set of experiments with a completely different stress state. Four point bend specimens have a wide area of constant high stress (see Figure 7) as opposed to the small area of concentrated stress in a 2-hole specimen.

The four point bend specimen used for fatigue test is very sensitive to microstructural features and the failure seeks out the dominant material discontinuity in the specimen test section. All the fatigue cracks were initiated at particles as observed in the experiments. Experimental testing performed for three stress levels (50, 55 and 60 Ksi) and the results are shown in Figure 8.

Fatigue analysis was performed to simulate the experimental conditions and the results were compared with test data. The manufacturing-induced residual stresses were also considered in the model. The same fatigue model calibrated with smooth bar testing as described above was used for the four point bend specimens.

The fatigue lives from the experimental work and the simulation model were compared to assess the effectiveness of the model. Statistical analysis at confidence level 95% was performed to determine whether the experimental data could reflect the simulation data. Figure 8 shows that the model predictions are within a 95% confidence bound of the actual test data.

CONCLUSIONS

This paper presents a method for predicting fatigue failure using a virtual prototyping software tool that allows the simulation of real material behavior. The method uses computer models to simulate the three-dimensional microstructure in which fatigue evolves. Damage, such as dislocations and cracks, is simulated as it grows and interacts with the surrounding microstructural constituents. Major inputs to the simulation are details on the grain structure properties of the material being simulated, the loading conditions on the material, and the damage accumulation mechanisms. Because grain structure properties are randomly distributed through any macro-sized structure, Monte Carlo simulation is used to give a probabilistic distribution of fatigue failure outcomes over the operating life of the structure.

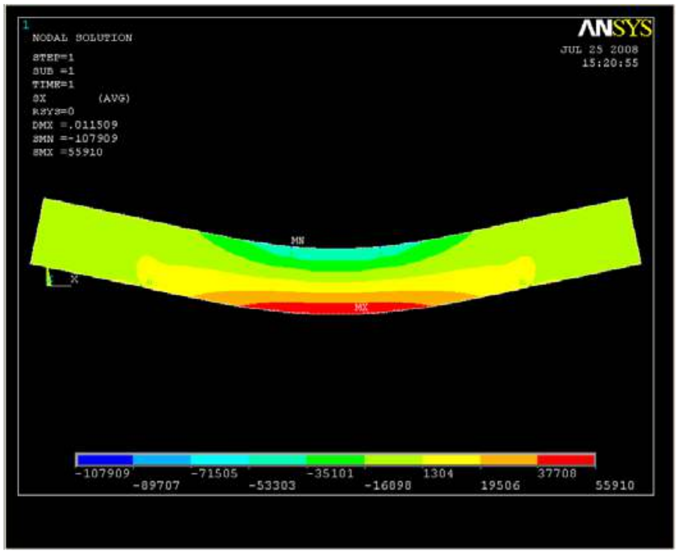


Figure 7: FEA model for the flat plate specimen. Observe the rapid stress change from the lower to upper surface.

This sophisticated analysis method can predict the fatigue life of complex component shapes under complex loading. By using a unique micromechanics approach, the stress cycles are applied to the material grain level. The same material model can be used with different component shapes and load sequences without modification. This capability has tremendous advantages for aerospace and industrial clients. Designers have a better capability for fatigue prediction allowing for more accurate designs. Material and processes engineers can assess the impact of minute changes in manufacturing. Sustainment engineering can assess risk of failure with actual measured mission loadings.

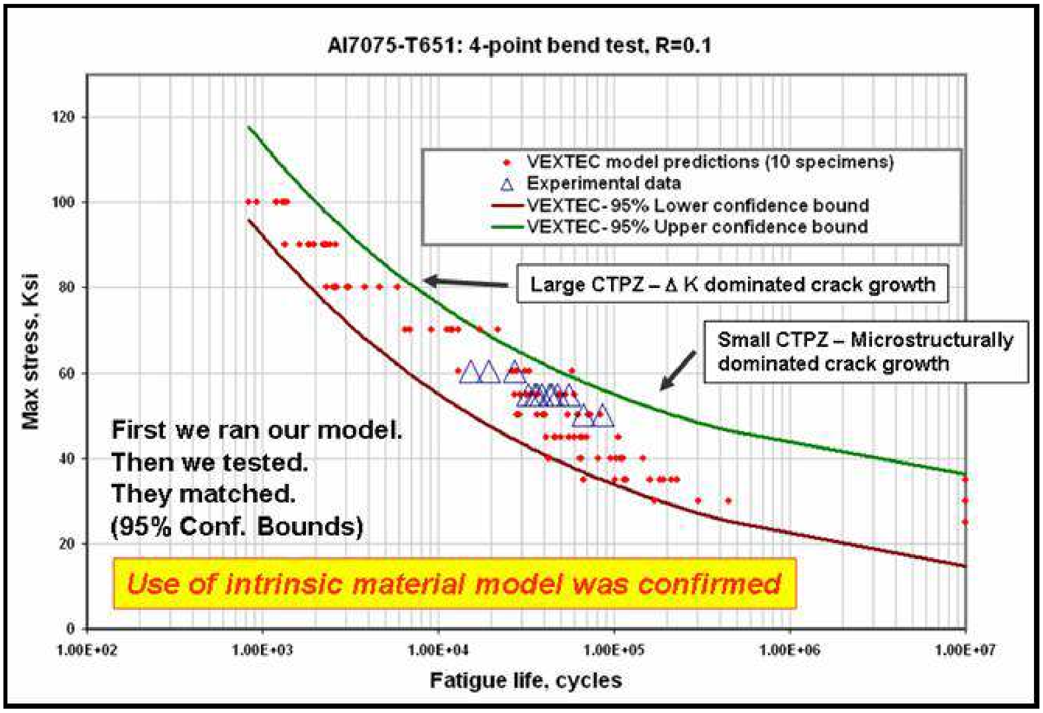


Figure 8: Comparison of test results from four point bend testing. Test results match model prediction within 95% confidence.

The modeling process is keenly applicable to Condition Based Maintenance Systems and Prognostics and Health Management Systems. Through accurate data collection, these fatigue models would predict an hour by hour damage accumulation and probability of failure of the structure. This will improve and support condition based structural inspection, life cycle cost reductions and safety improvement.

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