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TMF

Testing and Analysis Solutions

Material Modeling and Durability

ThermoMechanical Fatigue (TMF) analysis is a truly material-centric problem. Typically TMF occurs in high-value power-producing applications, either by individual component cost (turbines) or by volume (automotive powertrain). NW Numerics believes that proper analysis of TMF requires a very robust treatment of the time and history dependant behavior of the materials over a broad range of temperatures in order to be handled properly. Therefore the use of advanced constitutive equations in the structural FEA modeling is a requirement. Some examples of Z-mat solutions follow:

Grey Iron Z-mat has the state-of-the-art in material models for cyclic TMF loading of grey and CGI iron. This can be combined with a Z-post durability analysis using Smith-Watson-Topper fatigue parameter based on the viscoplastic strain range

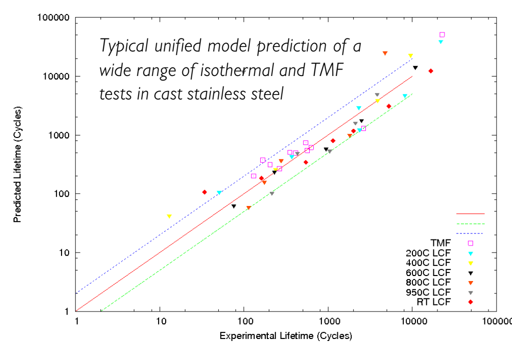
SiMo Irons Z-mat has an excellent framework for unified viscoplastic treatment of SiMo irons which typically see enormous changes in properties over a typical loading history (e.g. manifold or turbo housing). These materials have interesting ductility patterns which affect the fatigue modeling, with a rise in durability slightly above room temperature, then potentially a severe sensitivity to tensile yielding at intermediate temperatures, followed by a continued increase in ductility above 700C reaching enormous strains to failure. If the viscosity and strength changes are taken into account, a Sehitoglu model applied to the plastic range with particular care to find out of phase loadings where ductility is affected by oxidation.

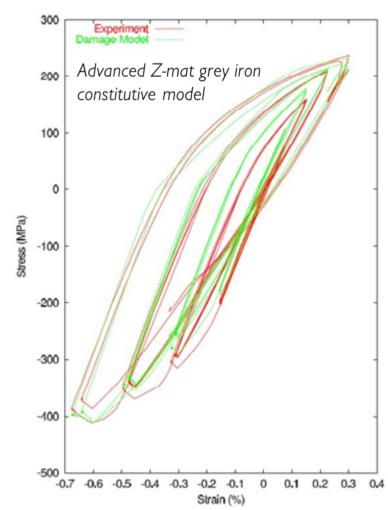
Cast Aluminum Z-mat fully incorporates aging effects in the general viscoplastic models. So these materials are well predicted using a 2 or more term kinematic hardening model with viscocity function and time/temperature based changes in hardening modulus and drag stress. Viscocity effects causing higher plastic strains can compensate partially for life reduction at high temperature, but creep damage in tensile loading also should be treated. Either our modified Neu-Sehitoglu or the Chaboche TMF model can be used with a plastic strain driven fatigue part.

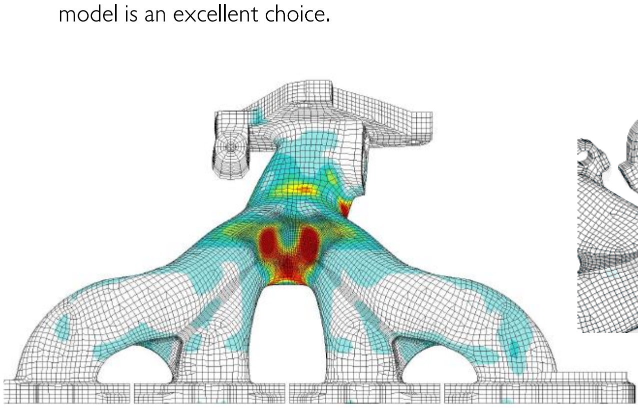
Stainless Steels Stainless steels are good against oxidation, and can hold stress at elevated temperature (unlike SiMo irons which relaxation of stress is inevitable at high temperature). The stress applied at elevated temperature turns out to be the damaging mechanism, and low-cycle fatigue strength and low strain rate ductility decrease at elevated temperature. These materials are well analyzed with the Z-mat gen_evp unified viscoplastic model with static recovery, and a plastic strain range based fatigue parameter utilizing strength based on the maximum cycle temperature.

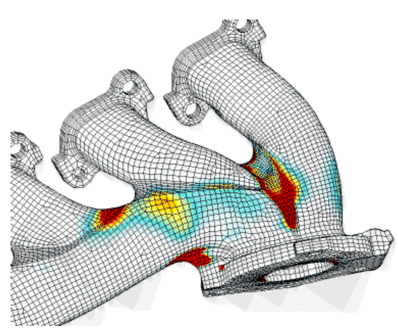
Superalloys Superalloys are typically used in stress-carrying elevated temperature and can have important aging effects due to the high percentage of alloying elements and their precipitates. The Z-mat gen_evp model with aging incorporated combined with the Chaboche stress based TMF model is an excellent choice.

- *Extensive experience with Powertrain, Power Generation, and Aerospace TMF*
- *Full capability for all relevant aspects of material testing*
- *Solutions for more robust constitutive modeling of many materials under TMF*
- *Analysis tools for production durability analysis*



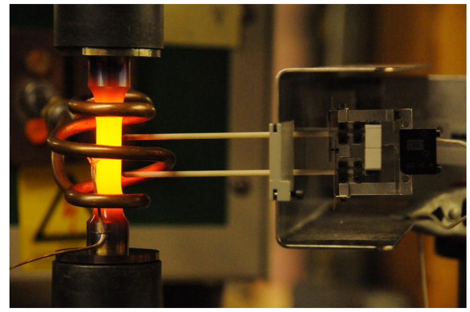


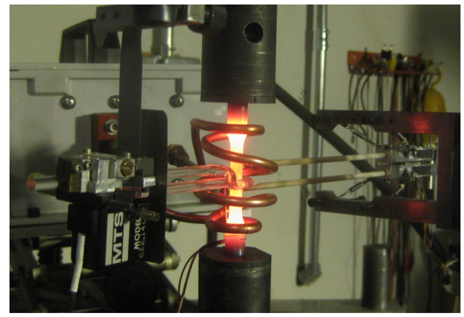


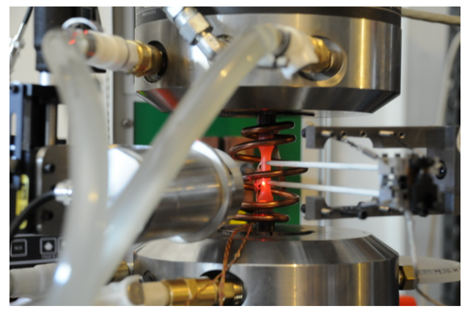


Testing / Analysis Programs

- Elastic modulus / Poisson tests
  - For high temperature quite tricky (middle photo).
  - The most basic material property is sometimes the most difficult to obtain.. Sometimes this is the material itself.
- Tensile tests - Typically lowest cost test but consumes material
  - Modulus (low res), 0.2% Yield, UTS, Elongation, Area Reduction
  - Multiple strain rates give strain rate influence
  - Full curve a robust standard for material model fitting - VALUABLE
- Model calibration tests
  - Typically non-standard, mix up loading to be complex & robust standards for model performance
  - E.g. cyclic test with hold, interrupted creep, tensile with hold, expanding strain ranges…
- Low cycle fatigue (LCF) tests
  - Strain controlled cycles to failure
  - Typically ranges can wander some… Total strain, plastic strain, stress range all somewhat variable depending on material…
  - Picking fixed loading (e.g. plastic strain range) can be done but requires lower strain rate.. And precludes other modeling choices.
- Thermo-mechanical fatigue (TMF)
  - Tests with continuously controlled temperature and mechanical loading
  - Hold times at max temperature show exposure influence
  - In-phase loading (tension at high temp) shows influence of creep
  - Out-of-phase loading (comp at high temp) shows oxidation influence
- Strain range partitioning (SRP)
  - Follows an old NASA model - isothermal but also identifying in/out of phase characteristics
  - Expensive because of hold times and test procedure.. Similar to TMF costs
- Creep testing
  - Static load at high temperature to failure
  - Time consuming but not excessively expensive
  - Known for material variations..
  - Very good for high temperature material model calibration for reasons similar to tensile tests







Typical Material Testing Matrix Development

- Testing program involves e.g. 120 specimens, with a combination of “baseline” mechanical tests, LCF, Creep, and Thermomechanical fatigue
- Temperature ranges from 23-920C with 12 different levels
- TMF tests with 100-700, 100-820C temperature levels
- Every test is used to enhance the quality of the Z-mat material model (predicting stress-strain in the FEA model)
- This type of testing does not determine classical individually quantifiable material parameters (like “strength”).
- Success depends on interpretation and modeling analysis