

# ***First Approximation Unified Fatigue Models for Cryogenic 316 Stainless Steel and Elevated Temperature IN718 from Monotonic Material Properties***

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- Metadata analysis performed and data collected for 316L (and LN, LNH variants) stainless steel for cryogenic fusion applications.
- Strain-life low cycle fatigue (LCF) model created based on prior successful IN718 experience at room and elevated temperatures (dwell, TMF).
- Manson-Coffin, Ramberg Osgood principles applied for fully reversed conditions at 4K, 77K, 293K.
- Monotonic Brinell hardness based model evaluated as first pass approach to characterizing cyclic fatigue behavior.
- Results show conservative, but reasonable results; areas for improvement in the form of additional temperature dependency identified.

# Background

- 316L type austenitic stainless steels are used for structural applications in various locations of the tokomak.
- Main product forms are forgings and plates.
- Fatigue performance for different load conditions at various temperatures ranging from elevated to cryogenic constitutes an essential design property.
- Extensive literature search performed on 316L family of alloys (L, LN, LNH) to create design system for cryogenic applications.
  - 316L: low carbon
  - 316LN: low carbon, high nitrogen
  - 316LNH: low carbon, high nitrogen (> 0.2%)
- Majority of material taken from hot rolled plate, and machined into round bars between 6 and 10 mm in diameter. At least three different heats of material were used per temperature for each curve.
- Fully reversed (R = -1) design curves generated for 4K, 77K, and 293K; based on a modified life-limited Manson Coffin Basquin equation; stress strain response given by the Ramberg Osgood relationship.
- Typical and min curves based on Boiler / Pressure Vessel Code (20X life, 2X stress).

	wgt%
C	0.03
Si	0.75
Mn	2
P	0.045
S	0.03
Ni	12
Cr	17
Mo	2.5
N	0.13

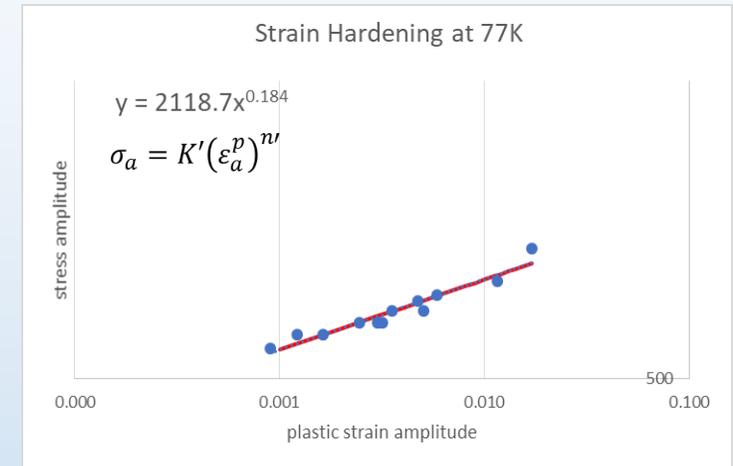
Generic 316SS chemistry  
 316L: N ≤ 0.1%  
 316LN: N = 0.1-0.3%  
 316LNH: N ≥ 0.2%

- Strain response for a load controlled test for use in a e-N (strain life) model must use a constitutive model (Ramberg Osgood) derived cyclic stress strain data.
- Relates stress amplitude to plastic strain amplitude.

$$\sigma_a = K'(\varepsilon_a^p)^{n'}$$

$$\rightarrow \varepsilon_a^p = \left(\frac{\sigma_a}{K'}\right)^{1/n'}$$

$$\rightarrow \varepsilon_a = \frac{\sigma_a}{E} + \left(\frac{\sigma_a}{K'}\right)^{1/n'}$$

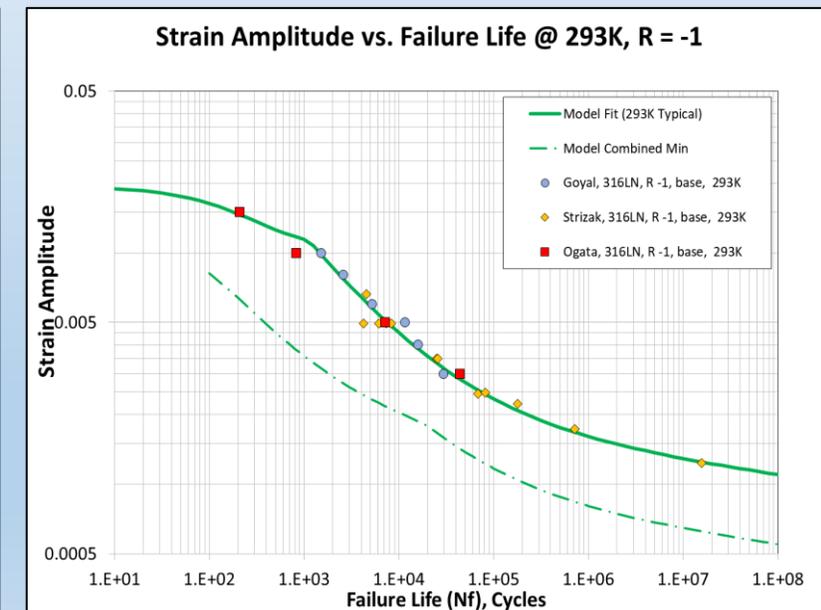
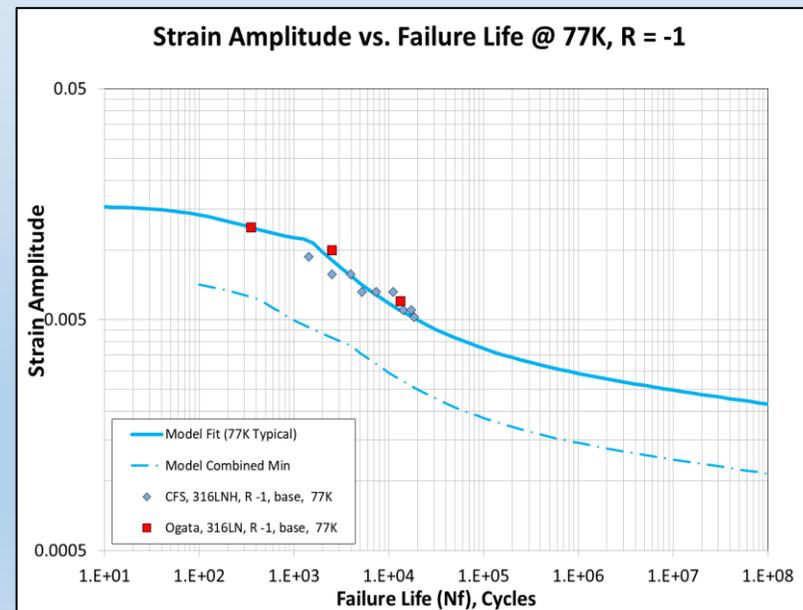
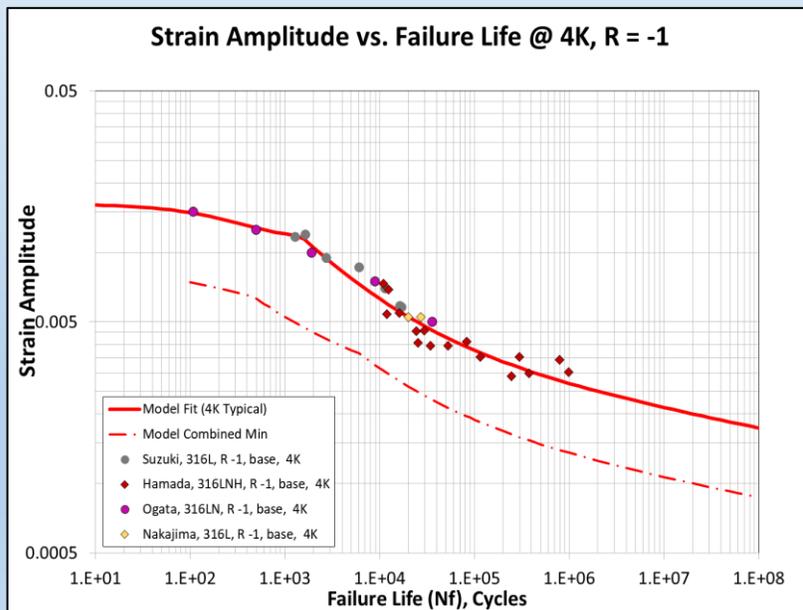


- Fatigue life calculated using the Manson Coffin Basquin double power law equation.
- Strength and ductility coefficients  $\sigma_f'$  and  $\varepsilon_f'$  are based on the UTS and elongation limit at temperature.
- Exponents b and c are optimizable constants.
- Incorporates a “cutoff” value D, incorporated in response to high-load strain controlled data which showed a significant deviation from power law behavior below 10,000 cycles (see next slide).

$$\frac{\Delta\varepsilon_{R=-1}}{2} = \frac{\sigma_f'}{E} (\max(2N_f, D))^b + \varepsilon_f' (\max(2N_f, D))^c ; \quad D = n_1 e^{\left(-\frac{N_f}{n_3}\right)} + n_2 \left(1 - e^{\left(-\frac{N_f}{n_3}\right)}\right)$$

- $N_f$  must be solved iteratively if the stress / strain conditions are known and target life is not.

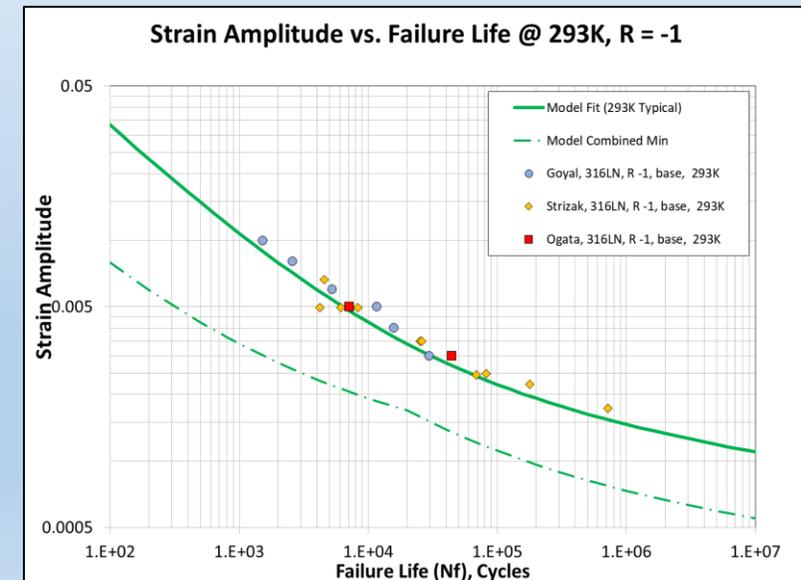
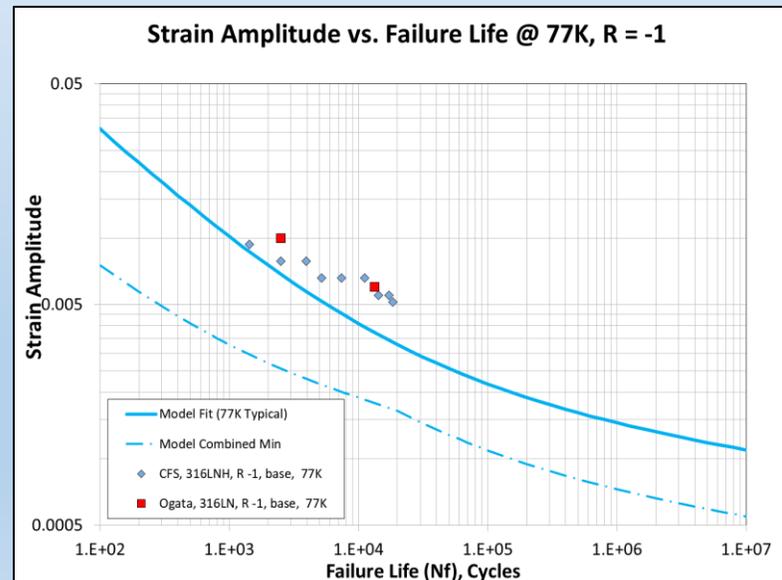
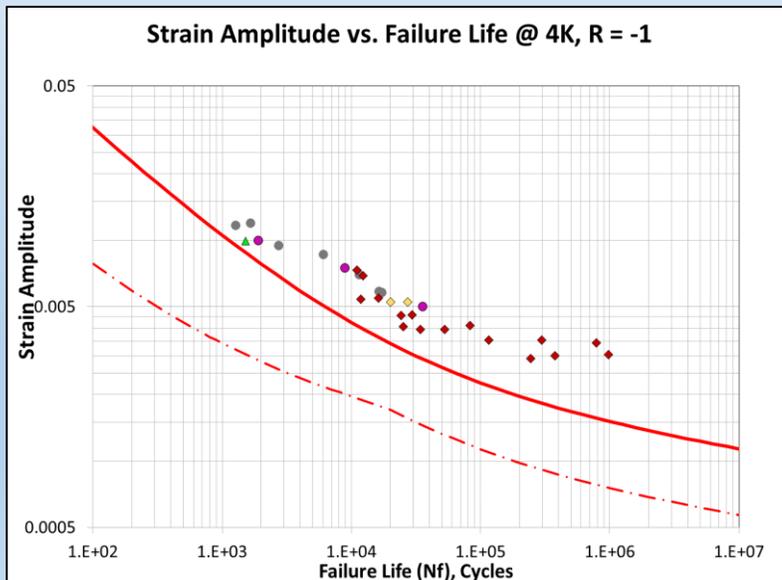
- 4K, 77K model makes use of load and strain controlled data; 293K exclusively strain controlled.
- Standard Manson Coffin curve modified based on behavior of high stress / strain fatigue data.
- Min curve represents the minimum of 2X stress debit and 20X life debit.
- Model fit at 4K also shows strong consistency with Nakajima, et al which provided the basis for the 4K JSME design curve.
- Min curve adjusted based on the presence of data that suggests a stress cutoff at lower lives.
- 316L+ model shows typical to min scatter of 4X based on a lognormal distribution of A/P values.



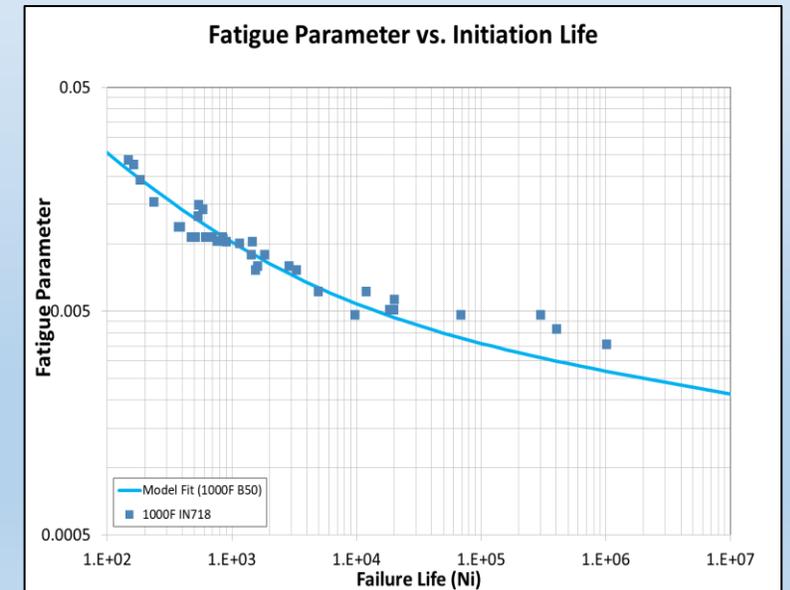
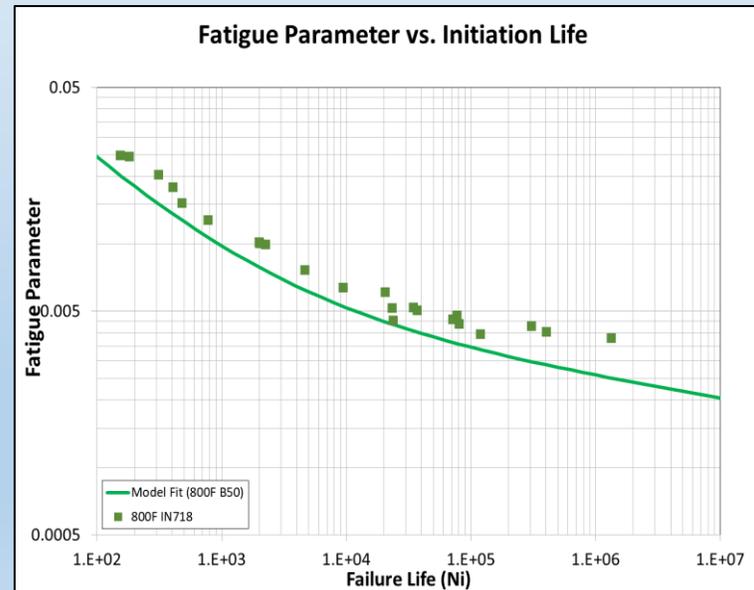
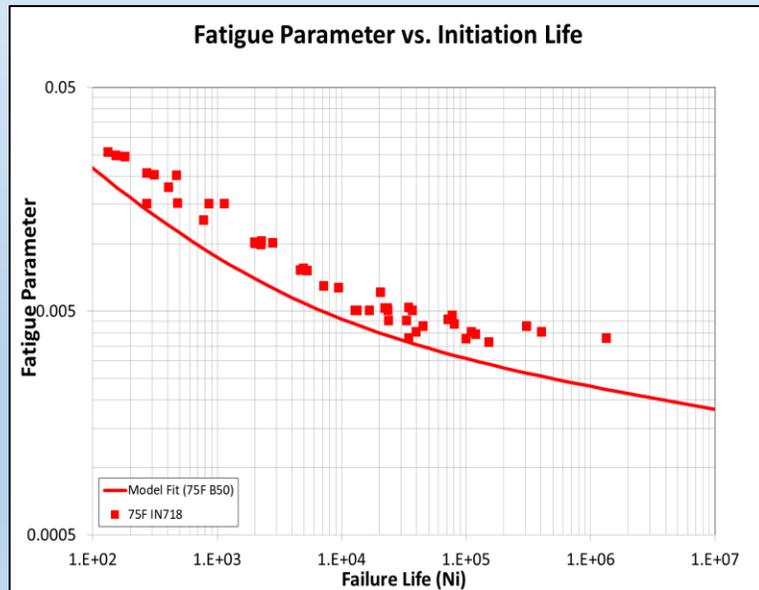
- Hartman, Glinka: fatigue behavior can be approximated through the use of monotonic properties.
- Correlation with Brinell hardness, elastic modulus identified as overall most effective for steels.
- Based on a study of 69 steels total.
- Evaluation of 316SS database shows conservative fit to cryo data, good room temperature fit.

$$\frac{\Delta \varepsilon}{2} = \frac{4.25(HB) + 225}{E} (2N_f)^{-0.09} + \frac{0.32(HB)^2 - 487(HB) + 191000}{E} (2N_f)^{-0.56}$$

$$\varepsilon_a = \varepsilon_e + \varepsilon_p = \frac{\sigma_a}{E} + \left(\frac{\sigma_a}{K'}\right)^{1/n'} \quad n' = \frac{b}{c} \quad K' = \frac{\sigma_f}{\varepsilon_f^{n'}}$$



- Hardness fit on previous page shows little variation as a function of temperature since modulus does not change between 4K-293K.
- In the case of IN718, modulus changes sufficiently as a function of temperature to allow the curves to “follow” the LCF behavior more closely.
- Hardness method does a better job fitting the data for IN718; clear that some form of temperature is necessary to collapse data.



# Conclusions

- Stainless steel 316L+ (-L, -LN, -LNH variants) fully reversed strain-life fatigue model has been developed for cryogenic fusion applications.
- Results at 4K are consistent with JSME design curves at  $N > 10,000$ ; new “cutoff” added based on observations.
- Additional data at alternate R values, geometries (notches), and temperatures needed for a fully “unified” model.
  
- Monotonic Brinell hardness approach successfully applied to 316L+ and IN718, with resulting e-N curve being conservative for both materials.
- Lack of modulus variation in 316 prevents much change in resulting life curves, causing additional conservatism.
- Possible areas of improvement include building temperature dependency using UTS or elongation normalized to room temperature.
- Evaluation using other materials (steels, Ti, Ni, etc.) and temperatures would provide additional insight into how to implement approach on a broader scale.

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