Determination of Material Parameters

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Abstract: The objective of the following paper is to provide guidance on the determination of material parameters required to perform TURBOlife durability assessments. In particular, the fitting of monotonic stress-strain test data and low cycle fatigue test data to the well known Ramberg-Osgood and the Coffin-Manson equations, respectively.

Keywords: Alloy 617, Coffin-Manson, Cyclic, Damage, Fatigue, Monotonic, Rambergy-Osgood and TURBOlife.

1. Introduction

The objective of the following paper is to provide guidance on the determination of material parameters required to perform durability assessments, such as available in fe-safe/TURBOlife™. In particular, this paper focuses on the fitting of monotonic stress-strain test data and low cycle fatigue test data to the well known Ramberg-Osgood and the Coffin-Manson equations, respectively. Material modeling theory for stress-strain behavior and initiation of fatigue crack growth is summarized in Section 2 and Section 3 respectively. Determination of material modeling parameters for Alloy 617 using published experimental test results is described in Section 4.

The fe-safe/TURBOlife™ software is a powerful, comprehensive and easy-to-use suite of creep-fatigue analysis software for Finite Element Analysis (FEA) results. It directly interfaces to leading suites of FEA software and is supplied complete with a material database to which users can add their own data. TURBOlife durability assessments are being used increasingly in the powertrain industry where creep and creep fatigue interaction is prevalent in automotive exhaust components and turbocharger impellers. Subsequently, preparation of the TURBOlife material input data for Alloy 617, when fit to the Ramberg-Osgood and the Coffin-Manson equations defined in this paper, is demonstrated in Section 5.

2. Stress and Strain Properties

A simple uni-axial tensile test is commonly used to determine the engineering stress-strain curve which represents the time-independent tensile behaviour of materials. The tensile test involves subjecting a polished cylindrical specimen to a monotonically increasing elongation while simultaneously measuring the uni-axial tensile force. Generally, tensile tests are conducted in a well controlled environment to provide a constant temperature and tested at a constant strain rate, and is continued until the specimen failure (i.e. complete separation). The measured load and corresponding elongation from the test are used to construct an engineering stress-strain curve similar to that shown in Figure 1.

2.1 Young's Modulus

Providing the elastic limit (Point A in Figure 1) of a material is not exceeded the load is directly proportional to the elongation (Points O-A) and the specimen will return to its original length if the load is removed. The Young's Modulus (E) is given by:

$$E = \sigma / \varepsilon \qquad \text{Equation 1}$$

Where: σ is stress
ε is strain

Engineering stress-strain curve must be interpreted with caution beyond the elastic limit (S_Y), since the specimen dimensions experience substantial change from their original values. Using the true stress ($\sigma = P/A$) rather than the engineering stress ($\sigma_{Eng} = P/A_0$) can give a more direct measure of the material's response in the plastic flow range. Therefore, the engineering stress and engineering strain (ε_{Eng}) must be converted in to true stress and true straining (ε) using the following equations:

$$\sigma = \sigma_{Eng} \times \left(1 + \varepsilon_{Eng}\right) \qquad \text{Equation 2}$$

$$\varepsilon = \ln\left(1 + \varepsilon_{Eng}\right) \qquad \text{Equation 3}$$

Where: S_Y is yield stress
P is applied load
A is true area
A_0 is original area

2.2 Monotonic Stress-Strain Properties

The idealisation of elastic-perfectly plastic material model provides the extreme material response where, once the yield stress has been reached there is unlimited plastic flow in the material. This will be seen as a horizontal line in the σ-ε curve intercepting O-A at Point A in Figure 1. While this may seem to be an unrealistic material model, it is conservative for design purposes and it therefore plays a central role in the theory of plasticity of structures.

In simple terms the material plasticity model describes the permanent deformation of a structure, where, after loading and subsequent unloading the structure is found to have been distorted from its initial shape. Permanent deformation occurs in real materials if the load imposed upon the structure causes the stress to exceed the yield stress introducing elastic and plastic strains. Subsequent loading above this stress causes additional plastic strain which is not recoverable upon unloading.

According to the classical theory of plasticity, the plastic strain is proportional to the derivative of the yield function with respect to the stresses. The incremental theory of plasticity assumes the total irreversible strain can be obtained as the sum of the strain increments where the inelastic straining is time independent. The basic principle is that the total strains (ε) can be broken-down into an elastic strain ($\varepsilon_{elastic}$) and a plastic (inelastic) strain (ε_{in}). The equation for $\varepsilon_{elastic}$ and a simple estimate of ε_{in} are provided in Equations 4 and 5 respectively.

$$\varepsilon_{elastic} = \frac{\sigma}{E} \qquad \text{Equation 4}$$

$$\varepsilon_{in} = \left(\frac{\sigma}{A}\right)^{1/n} \qquad \text{Equation 5}$$

Where: A is Ramberg-Osgood coefficient for monotonic σ-ε curve
n is Ramberg-Osgood power for monotonic σ-ε curve

Therefore, the stress-strain curve of a material can be approximated by combining $\varepsilon_{elastic}$ and ε_{in} in the following equation, known as the Ramberg-Osgood equation:

$$\varepsilon = \frac{\sigma}{E} + \left(\frac{\sigma}{A}\right)^{1/n} \qquad \text{Equation 6}$$

2.3 Cyclic Stress-Strain Properties

Under cyclic load-unload or load compression behaviour, if the initial stress is greater than the monotonic yield stress, plastic deformation will occur during the first cycle. If this load cycle is maintained (to provide a hysteresis loop) the point at which the material yields may increase or decrease. This is a result of the evolution of slip bands and is known as cyclic hardening and softening respectively. For materials, which cyclically harden or soften, subsequently deformation may lead to the condition where the local cyclic stress range is less than the saturated cyclic yield stress (depending on if the stress is load or strain controlled). Under such conditions, the deformation response may become elastic (termed shakedown) and assessment calculations are greatly simplified. For cyclically softening materials, the development of the shakedown condition occurs less often.

Because of these potential complexities it is common to use analytical models. However, cyclic stress-strain (CSS) properties are required to perform such non-linear finite element analysis of components. The response of materials experiencing cyclic strains in service depends on their inherent behaviour and whether such behaviour can be altered by prior loading or after periods of service ageing.

These CSS properties may be conveniently described by the cyclic form of the Ramberg-Osgood relationship [Equation 7], which defines the locus of the tips of the stable hysteresis loop curves (i.e. tips of closed σ-ε loop). Inelastic finite element analysis and TURBOlife prefer to work in terms of semi-ranges of stress and strain shown in Figure 2 (i.e. dotted line). Equation 7 describes either the tension or compression arm of the S-like locus, with the origin at the original starting point. In this case, and provided the tension and compression stress amplitudes are equal, the strain range, $\Delta\varepsilon$, can be given by:

$$\frac{\Delta\varepsilon}{2} = \frac{\Delta\sigma}{2E} + \left(\frac{\Delta\sigma}{2K_m}\right)^{1/\beta} \qquad \text{Equation 7}$$

Where: K_m is Ramberg-Osgood coefficient for cyclic σ-ε curve
β is Ramberg-Osgood power for cyclic σ-ε curve
$\Delta\sigma$ is cyclic stress range

3. Fatigue Life Curve

Repeatedly subjecting of a metal component to either load-controlled or strain-controlled cycling may result in a fatigue failure. Strain-controlled fatigue tests are normally used to determine the cyclic behaviour of materials. This is pertinent to pressure vessel component crack initiation as these often results from low cycle fatigue, from strain-controlled thermal loading. The fatigue test specimen is generally hour-glass shaped and is subjected to uniaxial push and pull at a constant temperature. The fatigue tests are usually conducted at a constant strain rate and constant strain range, with zero mean strain.

The Coffine-Manson equation uses the energy dissipation as a failure criterion. The number of cycles to failure (N_0) can be calculated from the strain range (Δε) using the method of universal slopes:

$$\frac{\Delta\varepsilon_{in}}{2} = \varepsilon_f \left(2N_0\right)^C \quad \& \quad \varepsilon_f = \ln\left(\frac{100}{100 - RA}\right) \qquad \text{Equation 8}$$

Where $\Delta\varepsilon_{in}$ is the plastic strain range, $2N_0$ is the number of load reversals to initiate crack growth and ε_f is the fatigue ductility coefficient being some fraction of the true fracture strain measured in the tension test (ε_f = 0.35 to 1.00). RA is the area of reduction at fracture [%] and C is the fatigue ductility exponent (typical range for C = -0.5 to -0.7).

Under elastic cycling the Basquin equation is given by:

$$\frac{\Delta\varepsilon_{elastic}}{2} = \frac{\sigma_f}{E}\left(2N_0\right)^B \quad \& \quad \sigma_f = \sigma_{UTS}\left(1 + \varepsilon_f\right) \qquad \text{Equation 9}$$

Where $\Delta\varepsilon_{\mathrm{elastic}}$ is the elastic strain range, σ_f is the fatigue strength coefficient approximated by the true fracture stress, σ_{UTS} is ultimate tensile strength, , B is the fatigue strength exponent (typical range for B = -0.06 to -0.14) and E is Young's modulus. The strain life (ε-N_0) curve is defined in TURBOlife using the combination Coffin-Manson equation:

$$\frac{\Delta\varepsilon_{total}}{2} = \frac{\sigma_f}{E}\left(2N_0\right)^B + \varepsilon_f\left(2N_0\right)^C \qquad \text{Equation 10}$$

Where: $\Delta\varepsilon_{total}$ is the total cyclic strain range

4. Example of Curve Fitting

Fully-reversed strain-controlled continuous-cycle fatigue testing have been conducted on Alloy 617 cylindrical test specimens at 850°C in air at two strain ranges, 0.3% and 1.0%. Fatigue test data, summarised in Table 1, obtained from Idaho National Laboratory report (Reference 1) has been utilised below to demonstrate the various curve fitting techniques.

4.1 Young's Modulus

Inelastic strain range ($\Delta\varepsilon_{in}$), given in Table 1, is defined as the width of the hysteresis loop at zero stress. Elastic strain range ($\Delta\varepsilon_{elastic}$), given in Table 2, is the total strain range (ε_{total}) minus the inelastic strain range. Stress strain range ($\Delta\sigma$), given in Table 2, is the maximum tensile stress ($\Delta\sigma_{max}$) minus the minimum compressive stress ($\Delta\sigma_{min}$) obtained from Table 1. As the Young's Modulus (E) is defined as stress divided by elastic strain, the values given in Table 2 have been determined. For example, specimen 416-9 is shown below:

$$E = \frac{\Delta\sigma}{\Delta\varepsilon_{elastic}} = \frac{517.4}{0.003105} = 166{,}634 \quad \mathrm{MPa}$$

An average value of Young's Modulus (i.e. 172,830.8 MPa) has been utilized to determine the monotonic and cyclic stress-strain curves.

4.2 Monotonic and Cyclic Stress-Strain Curves

A schematic diagram of the fatigue σ-ε loops at 10 cycle and the monotonic stress-strain curve is shown in Figure 2. The monotonic stress-strain curve intercepts the tips of the fatigue σ-ε loops at 10 cycles the maximum tensile stress (i.e. points A and B in Figure 2). Similarly, the cyclic stress-strain curve intercepts the tips of the fatigue σ-ε loops at midlife the maximum tensile stress. The fatigue test data required to determine the monotonic and cyclic stress-strain parameters are summarised in Table 3.

4.2.1 Tensile Properties

Knowing the applied stress and inelastic strain values at two points on the tensile monotonic stress-strain curve, the monotonic stress-strain parameters (using Equation 5 and rearranges in terms of '*n*' & '*A*') can be determined as:

$$n = \frac{\log(260.6) - \log(179.6)}{\log(0.003477) - \log(0.000467)} = 0.185456$$

$$A = \frac{260.6}{0.003477^{0.185456}} = 744.882 \quad \mathrm{MPa}$$

Similarly, the tensile cyclic stress-strain parameters (using Equation 7 and rearranges in terms of 'β' & 'K_m') can be determined as:

$$\beta = \frac{\log(269.9) - \log(199.8)}{\log(0.003318) - \log(0.000211)} = 0.109308$$

$$K_m = \frac{269.9}{0.003318^{0.109308}} = 503.8534 \quad \text{MPa}$$

A graphical comparison of tensile monotonic and cyclic stress-strain curves (Equation's 6 & 7) against the monotonic and cyclic test data (Table 1), as shown in Figure 3, demonstrates reasonable agreement.

4.2.2 Compressive Properties

Knowing the applied stress and inelastic strain values at two points on the compressive monotonic stress-strain curve, the monotonic stress-strain parameters (using Equation 5 and rearranges in terms of '*n*' & '*A*') can be determined as:

$$n = \frac{\log(265.6) - \log(174.1)}{\log(0.003477) - \log(0.000467)} = 0.210304$$

$$A = \frac{265.6}{0.003477^{0.210304}} = 873.8492 \quad \text{MPa}$$

Similarly, the tensile cyclic stress-strain parameters (using Equation 7 and rearranges in terms of 'β' & 'K_m') can be determined as:

$$\beta = \frac{\log(273.5) - \log(197.9)}{\log(0.003318) - \log(0.000211)} = 0.117544$$

$$K_m = \frac{273.5}{0.003318^{0.117544}} = 535.0874 \quad \text{MPa}$$

4.3 Fatigue Life Curve

In order to determine the fatigue curve parameters (C, ε_f, B & σ/E), it is necessary to breakdown the fatigue equation (Equation's 8 & 9) in to the elastic strain and the inelastic strain terms, namely:

$$\frac{\Delta\varepsilon_{elastic}}{2} = \frac{\sigma_f}{E}(2N_0)^B$$

$$\frac{\Delta\varepsilon_{in}}{2} = \varepsilon_f (2N_0)^C$$

Next the elastic strain and the inelastic strain terms are then converted in to logarithmic terms, namely:

$$\log(\Delta\varepsilon_{elastic}/2) = \log(\sigma_f/E) + B \times \log(2N_0)$$
$$\log(\Delta\varepsilon_{in}/2) = \log(\varepsilon_f) + C \times \log(2N_0)$$

The fatigue test data (Table 1) has been converted in to logarithmic values (Table 4), and then plotted on Figure 4. Linear curve fitting of the log($\varepsilon_{elastic}$/2) data and the log(ε_{in}/2) data enables the fatigue curve parameters to be determined:

$$\log(\sigma_f/E) = -2.468 \quad and \quad \sigma_f/E = 10^{-2.468} = 0.003404$$
$$\therefore \sigma_f = 172{,}830.8 \times 0.003404 = 588.316\ MPa$$
$$B = -0.0986$$
$$\log(\varepsilon_f) = 0.7458 \qquad and \quad \varepsilon_f = 10^{0.7458} = 5.56929$$
$$C = -1.035$$

Graphical comparison of fatigue life curve (Equation 10) against the fatigue test data (Table 1), shown in Figure 5, which clearly demonstrates good agreement.

5. Input Data

An example of writing a user material database for the fe-safe/TURBOlife software is described below. TURBOlife material parameters, including the text file keywords, are defined in Section 8.10 of the user manual (Reference 2). Input data for Alloy 617 summarized in Appendix uses the following keyword:

Tensile properties	`POISSONS-RATIO, 0.2%-PROOF-STRESS(MPa)& ULTIMATE-TENSILE-STRENGTH(MPa)`
Young's modulus	`YOUNGS-MODULUS(MPa)`
Monotonic stress-strain properties	`K-MONOTONIC & n-MONOTONIC`
Cyclic stress-strain properties	`K'-TENSILE-CYCLIC, n'-TENSILE-CYCLIC, K'-COMPRESSIVE-CYCLIC & n'-COMPRESSIVE-CYCLIC`
Fatigue properties	`ef'-STRAIN-LIFE-CURVE, c-STRAIN-LIFE-CURVE, Sf'-STRAIN-LIFE-CURVE & b-STRAIN-LIFE-CURVE`

5.1 Tensile properties

Poisson's ratio, 0.2% proof stress, and tensile strength properties for Alloy 617 (References 3 & 4) are summarized in Table 5.

5.2 Young's modulus

Assuming that the temperature dependent values of mean Young's modulus (E) can be estimated from lower bound E. Knowing the experimental tensile value of E is 172,830 at 850^{o}C the correction factor is estimated below as 1.1045.

$$Correction = 172.83/153 = 1.1296$$

Therefore, the temperature dependent tensile values of A:

$$E_{20C} = 211 \times 1.1296 = 238.347 \quad GPa$$

$$E_{600C} = 169.5 \times 1.1296 = 191.468 \quad GPa$$

5.3 Monotonic stress-strain properties

Assuming that the monotonic exponent (n) is constant and the yield strain is 0.002 (0.2%). It is possible to estimate the temperature dependent values of A from the temperature dependent yield strength values (Table 5). Knowing the experimental value of A is 744.882 at 850°C the correction factor is estimated below as 1.1045.

$$A_{850C} = \frac{213}{0.002^{0.185456}} = 674.4$$

$$Correction = \frac{744.882}{674.4} = 1.1045$$

Therefore, the temperature dependent tensile values of A:

$$A_{20C} = \frac{367}{0.002^{0.185456}} \times 1.1045 = 1283.4$$

$$A_{600C} = \frac{239}{0.002^{0.185456}} \times 1.1045 = 835.8$$

5.4 Cyclic stress-strain properties

Assuming that the cyclic exponent (β) is constant and the yield strain is 0.002 (0.2%). It is possible to estimate the temperature dependent values of K_m from the temperature dependent yield strength values (Table 5). Knowing the tensile experimental value of K_m is 503.8534 at 850°C the correction factor has been estimated to be 1.1992.

$$K_{m\,850C} = \frac{213}{0.002^{0.109308}} = 420.1$$

$$Correction = \frac{503.8534}{420.1} = 1.1992$$

Therefore, the temperature dependent tensile values of K_m:

$$K_{m\,20C} = \frac{367}{0.002^{0.109308}} \times 1.1992 = 868.1$$

$$K_{m\,600C} = \frac{239}{0.002^{0.109308}} \times 1.1992 = 565.3$$

Knowing the compressive experimental value of K_m is 535.0874 at 850°C, and the correction factor has been estimated to be 1.2100.

$$K_{m\,850C} = \frac{213}{0.002^{0.117544}} = 442.2$$

$$Correction = \frac{535.0874}{442.2} = 1.2100$$

Therefore, the temperature dependent tensile values of K_m:

$$K_{m\,20C} = \frac{367}{0.002^{0.117544}} \times 1.21 = 921.9$$

$$K_{m\,600C} = \frac{239}{0.002^{0.117544}} \times 1.21 = 600.3$$

5.5 Fatigue life properties

Using the fracture strain (ε_f) and stress (σ_f) estimated in Table 5, it is possible to estimate temperature dependent from experimental fracture strain (ε_f) and stress (σ_f) values of 5.56876 and 588.316 (Section 4.3).

$$\varepsilon_{f\ 20C} = 5.56876 \times (0.872/0.280) = 17.3437$$

$$\varepsilon_{f\ 600C} = 5.56876 \times (0.605/0.280) = 12.0324$$

$$\sigma_{f\ 20C} = 588.316 \times (1458.2/410.8) = 2088.321\ MPa$$

$$\sigma_{f\ 600C} = 588.316 \times (1006.3/410.8) = 1441.145\ MPa$$

5.6 Creep properties

Although outside the scope of this paper, the creep strain and creep ductility in the attached Appendix, has been determined from creep test results for Inconel 617 (Reference 3). Creep-fatigue interaction diagram is representative of the behaviour of nickel alloys (Figure 24.12.5-3 in Reference 2).

6. References

1. Carroll, L, and Carroll, M, "Creep-Fatigue Behavior of Alloy 617 at 850 and 950^{o}C," Report INL/EXR-13-28886, Idaho National Lab., Idaho, USA, 2013.
2. fe-safe/TURBOlife User Manual.
3. McCoy, H.E., and King, J.F., "Mechanical properties of Inconel 617 and 618", Report ORNL/TM-9337, Oak Ridge National Laboratory, 1985.
4. "Haynes 617 alloy", Data sheet H-3171B, Haynes International Inc., 2008.

Table 1. Summary of fatigue test data (Reference 1).

Specimen	N_0 (Initiation)	$\Delta\varepsilon_{total}$	$\Delta\varepsilon_{in}$		σ_{Max} (MPa)	σ_{Min} (MPa)
			10 Cycles	Midlife		
43-6	9,900	0.003	0.000777	0.000389	176.5	-171.3
43-13	8,500	0.003	0.001016	0.000509	181.0	-174.3
43-22	10,000	0.003	0.001006	0.000370	181.3	-176.8
416-7	660	0.010	0.006733	0.006363	254.2	-260
416-9	620	0.010	0.006895	0.006601	258.1	-259.3
416-22	680	0.010	0.007233	0.006941	269.7	-277.7

Table 2. Determination of young's modulus.

Specimen	$\Delta\varepsilon_{elastic}$	$\Delta\sigma$ (MPa)	E (MPa)
43-6	0.002223	347.8	156,455
43-13	0.001984	355.3	179,083
43-22	0.001994	358.1	179,589
416-7	0.003267	514.2	157,392
416-9	0.003105	517.4	166,634
416-22	0.002767	547.4	197,832

Young's Modulus (E) = 172830.8 MPa (Average value)

Table 3. Determination of monotonic and cyclic Curve parameters.

$\Delta\varepsilon_{total}$	Average of 10 Cycle Test Data			Average of Midlife Test Data		
	$\Delta\varepsilon_{in}/2$	σ_{Max} (MPa)	σ_{Min} (MPa)	$\Delta\varepsilon_{in}/2$	σ_{Max} (MPa)	σ_{Min} (MPa)
0.003	0.000467	179.6	-174.1	0.000211	199.8	-197.9
0.01	0.003477	260.6	-265.6	0.003318	269.9	-273.5

Table 4. Determination of fatigue curve parameters.

Specimen	$\log(2N_0)$	$\log(\varepsilon_{in}/2)$	$\log(\varepsilon_{elastic}/2)$
43-6	4.296665	-3.71108	-2.88422
43-13	4.230449	-3.59431	-2.90466
43-22	4.301030	-3.73283	-2.88107
416-7	3.120574	-2.49737	-2.74029
416-9	3.093422	-2.48142	-2.76968
416-22	3.133539	-2.45961	-2.81545

Fatigue curve parameters: $C = -1.03497$, $\varepsilon_f = 5.56876$, $B = -0.09863$ & $\sigma_f/E = 0.003404$.

Table 5. Typical tensile properties for Alloy 617 (References 3 & 4).

Temperature	E [GPa]	$\sigma_{0.2\%}$ [MPa]	σ_{UTS} [MPa]	ν	Reduction in Area (%)	ε_f	σ_f [MPa]
20^oC	211	367	779	0.3	58.2	0.872	1458.2
600^oC	169.5	239	627	0.3	45.4	0.605	1006.3
850^oC	153	213	321	0.4	24.5	0.280	410.8

Note Fracture strain (ε_f) and stress (σ_f) estimated from reduction in area and UTS using Equations 8 and 9.

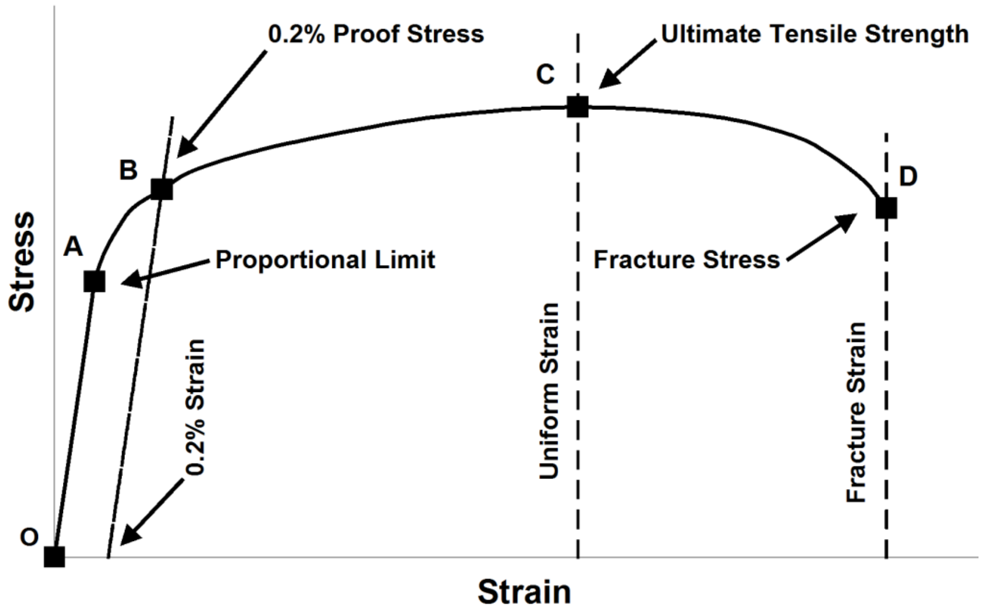

Figure 1. Schematic of engineering stress-strain curves.

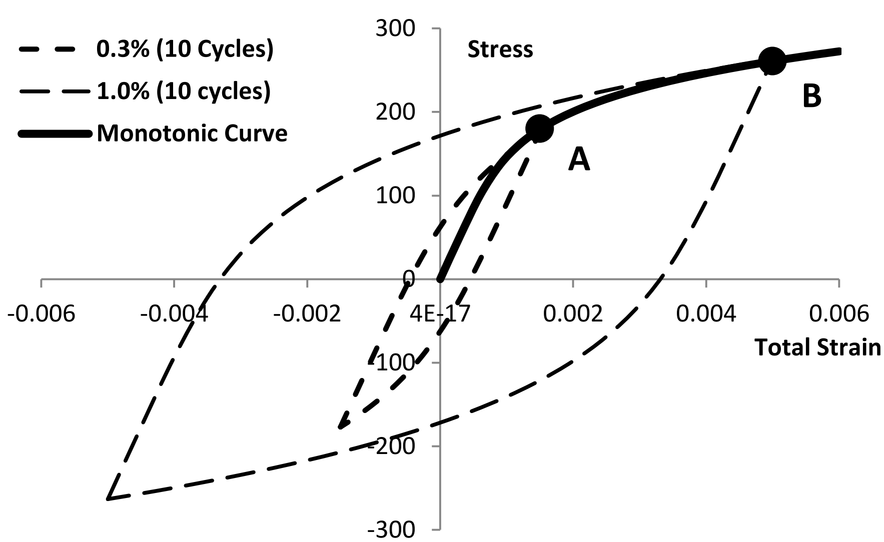

Figure 2. Determination of monotonic stress-strain curves at 850°C.

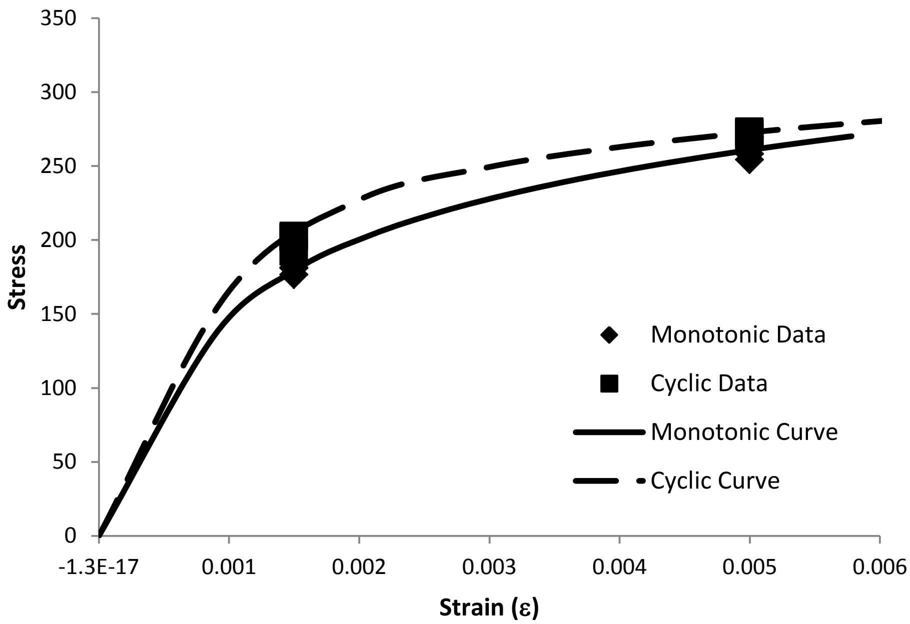

Figure 3. Comparison of stress-strain curves at 850°C.

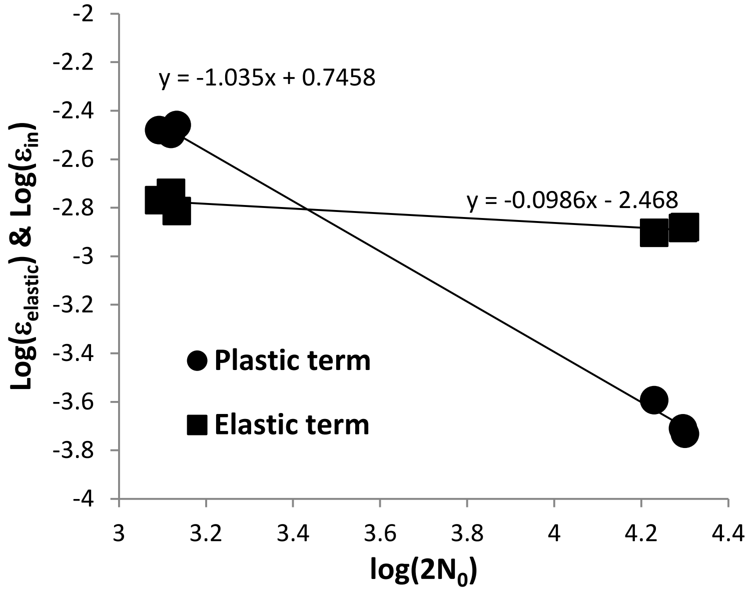

Figure 4. Determination of fatigue curve parameters.

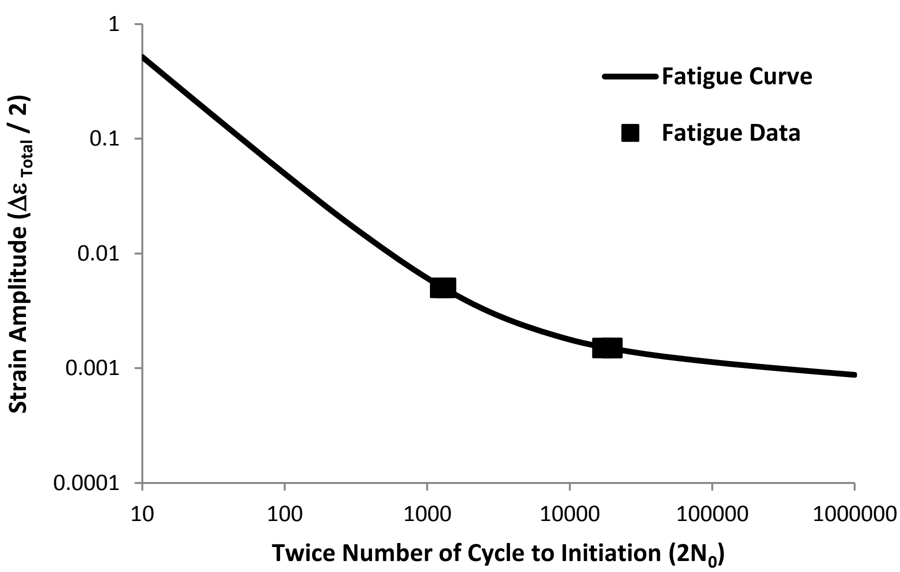

Figure 5. Comparison of fatigue curve against test data at 850°C.

Appendix – TURBOlife Input Data

```
MATERIAL DEFINITION FILE
# NOTES -9999 indicates a parameter is not set!
#       All items after a # are comments that will be ignored.
MATERIAL-NAME
Alloy 617
MATERIAL-CLASS
Nickel Alloy (Ductile)
ALGORITM
TURBOlife:-None
DISPLAY-UNITS
Metric - MPa, deg.C
CONSTANT-AMPLITUDE-ENDURANCE-LIMIT(2nf)
1e+015
TEMPERATURE-LIST(deg.C)
24
600
850
STRAIN-RATE-LIST(1/Hr)
0
TIME-LIST(Hrs)
1
10
100
1000
10000
POISSONS-RATIO
# T=24 C       T=600 C T=850 C
0.3     0.3     0.3
YOUNGS-MODULUS(MPa)
# T=24 C       T=600 C T=850 C
238347  191468  172830
0.2%-PROOF-STRESS(MPa)
# T=24 C       T=600 C T=850 C
367     239     213
ULTIMATE-TENSILE-STRENGTH(MPa)
# T=24 C       T=600 C T=850 C
779     627     321
ULTIMATE-COMPRESSIVE-STRENGTH(MPa)
# T=24C T=600 C T=850 C
```

```
-9999   -9999   -9999
K'-TENSILE-CYCLIC
# T=24C T=600 C T=850 C
868.1   565.3   503.85
n'-TENSILE-CYCLIC
# T=24C T=600 C T=850 C
0.109308       0.109308       0.109308
K'-COMPRESSIVE-CYCLIC
# T=24C T=600 C T=850 C
921.9   600.3   535.0
n'-COMPRESSIVE-CYCLIC
# T=24C T=600 C T=850 C
0.109308       0.109308       0.109308
SECANT-SLOPE-COMPRESSIVE-CYCLIC
# T=24C T=600 C T=850 C
-9999   -9999   -9999
SECANT-SLOPE-TENSILE-CYCLIC
# T=24C T=600 C T=850 C
-9999   -9999   -9999
MODULUS-OF-UNLOADING
# T=24C T=600 C T=850 C
-9999   -9999   -9999
K-MONOTONIC
# T=24C T=600 C T=850 C
1283.4  835.8   744.882
n-MONOTONIC
# T=24C T=600 C T=850 C
0.185456       0.185456       0.185456
damage-to-Harden(0->1)
0
ef'-STRAIN-LIFE-CURVE
# T=24C T=600 C T=850 C
17.3437 12.0324 5.56929
c-STRAIN-LIFE-CURVE
# T=24C T=600 C T=850 C
-1.035  -1.035  -1.035


Sf'-STRAIN-LIFE-CURVE
# T=24C T=600 C T=850 C
```

```
2088.3  1441.1  588.31
b-STRAIN-LIFE-CURVE
# T=24C T=600 C T=850 C
-0.0986 -0.0986 -0.0986
b2-STRAIN-LIFE-CURVE
# T=24C T=600 C T=850 C
-9999   -9999   -9999
2nf-ABOVE-WHICH-b2-IS-USED
# T=24C T=600 C T=850 C
-9999   -9999   -9999
ef'(pc)-STRAIN-LIFE-CURVE
# T=24C T=600 C T=850 C
-9999   -9999   -9999
c(pc)-STRAIN-LIFE-CURVE
# T=24C T=600 C T=850 C
-9999   -9999   -9999
ef'(cp)-STRAIN-LIFE-CURVE
# T=24C T=600 C T=850 C
-9999   -9999   -9999
c(cp)-STRAIN-LIFE-CURVE
# T=24C T=600 C T=850 C
-9999   -9999   -9999
ef'(cc)-STRAIN-LIFE-CURVE
# T=24C T=600 C T=850 C
-9999   -9999   -9999
c(cc)-STRAIN-LIFE-CURVE
# T=24C T=600 C T=850 C
-9999   -9999   -9999
COEFF-SWT-CAST-IRON-LIFE-CURVE
# T=24C T=600 C T=850 C
-9999   -9999   -9999
EXPONENT-SWT-CAST-IRON-LIFE-CURVE
# T=24C T=600 C T=850 C
-9999   -9999   -9999
CAST-IRON-OVERLOAD-THRESHOLD
# T=24C T=600 C T=850 C
0       0       0
CAST-IRON-OVERLOAD-COEFF-SWT-CAST-IRON-LIFE-CURVE
# T=24C T=600 C T=850 C
0       0       0
```

```
CAST-IRON-OVERLOAD-EXPONENT-SWT-CAST-IRON-LIFE-CURVE
# T=24C T=600 C T=850 C
0       0       0
CAST-IRON-OVERLOAD-Sf'-STRAIN-LIFE-CURVE
# T=24C T=600 C T=850 C
0       0       0
CAST-IRON-OVERLOAD-Sf'-STATIC-STRAIN-LIFE-CURVE
# T=24C T=600 C T=850 C
0       0       0
CAST-IRON-OVERLOAD-ef'-STRAIN-LIFE-CURVE
# T=24C T=600 C T=850 C
0       0       0
CAST-IRON-OVERLOAD-b-STRAIN-LIFE-CURVE
# T=24C T=600 C T=850 C
0       0       0
CAST-IRON-OVERLOAD-b2-STRAIN-LIFE-CURVE
# T=24C T=600 C T=850 C
0       0       0
CAST-IRON-OVERLOAD-c-STRAIN-LIFE-CURVE
# T=24C T=600 C T=850 C
0       0       0
CAST-IRON-OVERLOAD-2nf-ABOVE-WHICH-b2-IS-USED
# T=24C T=600 C T=850 C
0       0       0
BF-PROBABILITY
-9999
QMUF-PROBABILITY
-9999
IN-PHASE-THERMAL-FACTOR
-9999
OUT-OF-PHASE-THERMAL-FACTOR
-9999
PRE-SOAK-FACTOR
# T=24 C        T=600 C T=850 C
-9999   -9999   -9999   # t=1 Hrs
-9999   -9999   -9999   # t=10 Hrs
-9999   -9999   -9999   # t=100 Hrs
-9999   -9999   -9999   # t=1000 Hrs
-9999   -9999   -9999   # t=10000 Hrs
CREEP-ENDURANCE-LIMIT(2nf)
```

```
2e+007
CREEP-TEMPERATURE_THRESHOLD(deg.C)
500
CREEP-TABLE-A-STRAIN-LIMITS(Strain)
0
0.01
0.02
0.05
CREEP-TABLE-A-STRESSES(MPa)
# table for T=24 C
# t=1 Hrs      t=10 Hrs       t=100 Hrs      t=1000 Hrs     t=10000 Hrs
0       0       0       0       0       # Strain=0
519     464     409     354     299     # Strain=0.01
558     499     439     380     320     # Strain=0.02
607     542     477     412     347     # Strain=0.05
# table for T=600 C
# t=1 Hrs      t=10 Hrs       t=100 Hrs      t=1000 Hrs     t=10000 Hrs
0       0       0       0       0       # Strain=0
519     464     409     354     299     # Strain=0.01
558     499     439     380     320     # Strain=0.02
607     542     477     412     347     # Strain=0.05
# table for T=850 C
# t=0.001 Hrs  t=0.03 Hrs     t=0.1 Hrs      t=3 Hrs t=10 Hrs
# t=1 Hrs      t=10 Hrs       t=100 Hrs      t=1000 Hrs     t=10000 Hrs
0       0       0       0       0       # Strain=0
204     133     62      45      39      # Strain=0.01
218     141     65      46      40      # Strain=0.02
234     150     66      49      42      # Strain=0.05
CREEP-DUCTILITY-TABLE
# Rate (1/Hr)  Ductility
#       T=24 C  T=600 C T=850 C
1.0e-06        0.015   0.015   0.069
1.5e-05        0.015   0.015   0.069
1.0e-04        0.03    0.03    0.069
1.0e-03        0.1     0.1     0.025
1              0.1     0.1     0.025
CREEP-DAMAGE-INTERACTION-DIAGRAM
# Fatigue Damage(%)    Creep Damage (%)
0              100
8              8
```

```
100         0
WALKER_MSC_EXPONENT_POSITIVE
-9999
WALKER_MSC_EXPONENT_NEGATIVE
-9999
DEFAULT_KNOCKDOWN
-9999
```