NASA GRC Fatigue Crack Initiation Life Prediction Models

Vinod K. Arya
University of Akron
Akron, Ohio 44325

Gary R. Halford
National Aeronautics and Space Administration
Glenn Research Center
Cleveland, Ohio 441135
Ph: 216–433–3265
Email: gary.r.halford@grc.nasa.gov

Metal fatigue has plagued structural components for centuries, and it remains a critical durability issue in today's aerospace hardware. This is true despite vastly improved and advanced materials, increased mechanistic understanding, and development of accurate structural analysis and advanced fatigue life prediction tools. Each advance is quickly taken advantage of to produce safer, more reliable, more cost effective, and better performing products. In other words, as the envelop is expanded, components are then designed to operate just as close to the newly expanded envelop as they were to the initial one. The problem is perennial.

The economic importance of addressing structural durability issues early in the design process is emphasized. Tradeoffs with performance, cost, and legislated restrictions are pointed out. Several aspects of structural durability of advanced systems, advanced materials and advanced fatigue life prediction methods are presented. Specific items include the basic elements of durability analysis, conventional designs, barriers to be overcome for advanced systems, high-temperature life prediction for both creep-fatigue and thermomechanical fatigue, mean stress effects, multiaxial stress-strain states, and cumulative fatigue damage accumulation assessment.

NASA/CP—2002-211682

NASA-GRC Fatigue Crack Initiation Life Prediction Models

Vinod K. Arya
University of Akron

Gary R. Halford
NASA Glenn Research Center

5th Annual FAA/Air Force/NASA/Navy Workshop on the Application of Probabilistic Methods to Gas Turbine Engines

Holiday Inn Cleveland West
Westlake, OH
June 11-13, 2001

NASA/CP—2002-211682

NASA-GRC Fatigue Crack Initiation Life Prediction Models

Abstract

Metal fatigue has plagued structural components for centuries, and it remains a critical durability issue in today's aerospace hardware. This is true despite (a) the development of vastly improved and advanced materials, (b) increased mechanistic understanding, and (c) development of accurate structural analysis and advanced fatigue life prediction tools. Each advance is quickly taken advantage of to produce safer, more reliable, more cost effective, and better performing products. In other words, as the envelop of capability expands, components are designed to operate just as close, or even closer, to the newly expanded limits as they did to the initial ones. The problem is perennial.

The economic importance of addressing structural durability issues early in the design process is emphasized. Durability tradeoffs with performance, cost, and legislated restrictions are pointed out. Several unique aspects of structural durability of advanced systems, advanced materials and advanced fatigue life prediction methods are presented. Specific items to be discussed include the basic elements of durability analysis, conventional designs, barriers to be overcome for advanced systems, high-temperature life prediction for both creep-fatigue and thermomechanical fatigue, mean stress effects, multiaxial stress-strain states, and cumulative fatigue damage accumulation assessment. While not classified as being truly mechanistic models with a micromechanistic basis, they do contain aspects traceable to macroscopic, cause-and-effect phenomena. In their present form, the models are deterministic. Some examples of their application is presented. The models are awaiting efforts to be recast into probabilistic interpretation.

docProbabWorkshp2001grh052401

OUTLINE

0 - SETTING THE STAGE

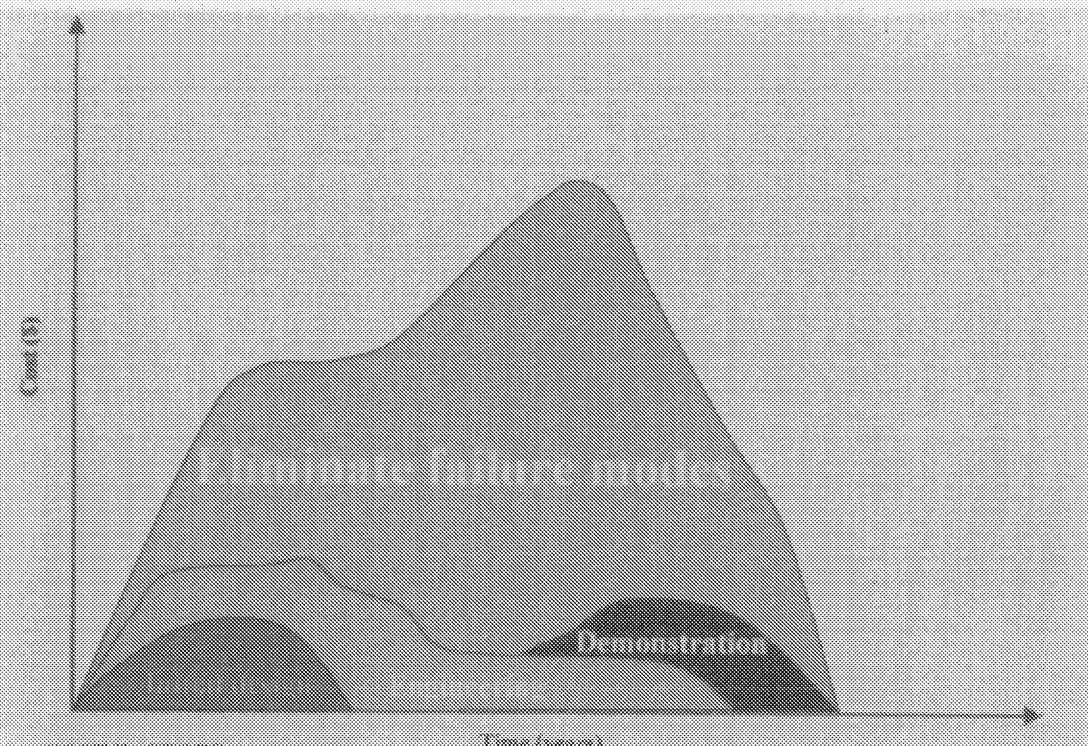
- Cost of Elimination of Failure Modes
- Structural Durability - Vs. Performance - Vs. Cost
  -- Durability, the poor step child
  -- Life prediction - a perennial problem (local vs. global)
  -- Prediction vs. Verification dilemma

0 - GLENN DURABILITY LIFING MODELS

- *Specific Material Models(for example, Oxidation, Coatings, Brittle Materials, etc.)*
- *Damage Mechanics Models*
- *Fatigue Crack Growth Models*
- *Multi-Factor Approach*
- Fatigue Crack Initiation/Early Growth Models
  -- Estimating Fatigue Curves (LCF & HCF)
  -- Modeling Effects of Variables
    - Mean stresses
    - Notches
    - Multiaxiality
    - Cumulative Fatigue Damage
    - Creep-Fatigue
    - Thermomechanical Fatigue
  -- Probabilistic Assessment of Non-Linear Effects

docProbabWorkshp2001grh052401

DEVELOPMENT COST DRIVEN BY FACTORS



COST FACTORS

Elimination Failure Modes	73%
Engineering	15%
Demonstration	10%
Initial Design	2%

Fig. Courtesy: Rockwell International

Primary Trade-off Troika Drivers

$\Uparrow$

PERFORMANCE

DURABILITY $\Rightarrow$

COST

$\Downarrow$

Overriding Requirements

Legislated / Public Outcry

⇑

SAFETY

ENVIRONMENTAL IMPACT

⇓

Elements of Durability Analyses

0 - Mission and Environmental Loading Analysis

0 - Global Structural Response Analysis

0 - Local Stress-Strain-Temp-Time Material Response Analysis

0 - Durability Failure Modes Analysis

0 - Damage Accumulation and Life Prediction Analysis

0 - Coupon & Hardware Testing for Model Calib./Valid./Verif.

0 - Mfg Quality Analysis and Non-Destructive Evaluation (NDE)

PEDESTRIAN DESIGNS

0 - Previous design experience

0 - Directly applicable rules of thumb

0 - Previous mission experience on similar hardware

0 - Extensive material property data bases

0 - Knowledge of all potential failure modes

0 - Knowledge of synergistic durability interactions

0 - Affordable ‘build-em’ and bust-em’ prototypes

BARRIERS TO ASSURED DURABILITY OF ADVANCED SYSTEMS

0 - Lack of previous direct experience/rules of thumb

0 - Limited material property data bases
-- long-term data bases unachievable in timely manner

0 - Ignorance of failure modes / synergistic interactions

0 - Low fidelity of damage accumulation/life models

0 - Prototypes too expensive to test or lead times too long

docProbabWorkshp2001grh052401

SURMOUNTING THE BARRIERS

- 0 - Accept up-front costs of designed-in durability
- 0 - Require critical minimum data bases
  - Early initiation of long-term testing
- 0 - Seek out failure modes & any synergism
- 0 - Capture the "physics" of damage accumulation
- 0 - Analytically model damage/life prediction
- 0 - Maximize durability information from each test
  - Fewer tests, however, decrease assessment of probabilities of failure
- 0 - Continuously update analytic models
- 0 - Take advantage of probabilistic analyses where possible

doc\ProbabWorkshp2001\grib052401

Glenn Program	Description
-PMUS	***Estimates Fatigue Resistance of Materials*** ***(Extensive use, e.g. Rocketdyne - SSME design)*** - Tensile Ductility & Tensile Strength - Cryogenic, Ambient, High Temperatures (10% Rule)
-LIFE	***Predicts Cyclic Life of Components Below Creep Regime*** - Multiaxiality via Triaxiality Factor - Mean Stress Correction
-PNOTCH	***Predicts Cyclic Life of Notched Components*** - Cyclic Stress-Strain Neuber Notch Analysis
-PDLDR	***Predicts Cumulative Damage Life of Components*** - Mission Loading History Analyzed - Predicts Crack Nucleation & Early Growth - Damage Curve Approach & Double Linear Damage Rule for Mission - Multiaxiality via Triaxiality Factor - Mean Stress Correction
-C-LIFE	***Predicts Cyclic Life of C-Section Components*** - Multiaxiality via Triaxiality Factor
-PSRPLIFE	***Predicts Cyclic Life of High-Temp Components*** ***(Adopted by FoMoCo - Manifold/Exhaust System Design)*** - Utilizes Raw Experimental Data - Total Strain Version of Strainrange Partitioning (SRP) - Isothermal Creep-Fatigue Interaction Assessment - Thermomechanical Fatigue Life Prediction - Bithermal Characterization - Cyclic Stress-Strain-Time-Temperature Characterization - Multiaxiality via Triaxiality Factor - Thermal Mean Stress Correction

docProbabWorkshop3301gr(b)052401

Non-Linear Cumulative Fatigue Damage Code- PDLDR

0 - Why the Fuss?
  - Example of Material Behavior

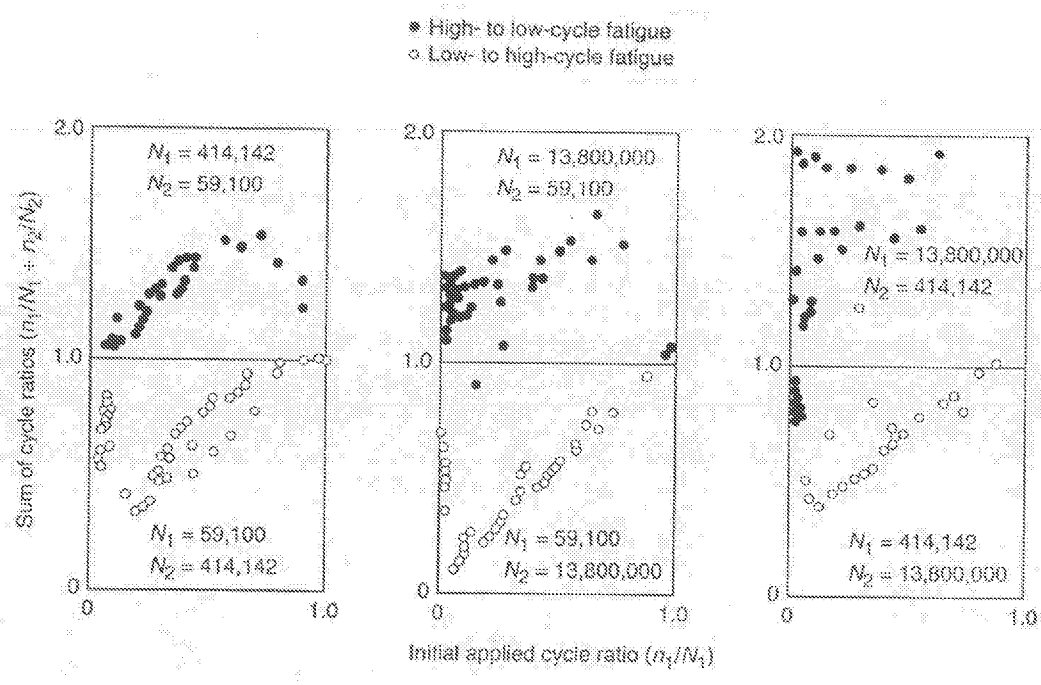
0 - Simple Models Developed
  - Require no more than Linear Damage Rule

0 - Sample Calculations
  - Idealized Space Shuttle Component

dscProbabWorkshp2001grf052401

Why the Fuss?

Classic Loading Order Effect in Two Load Level Cumulative Fatigue Damage Tests
British Aluminum Alloy D.T.D. 683



docProbsWorkshp2001grh052401

EXAMPLE APPLICATION - PDLDR

(Double Linear Damage Rule Vs. Linear Damage Rule)

Generic Space Shuttle Component using Haynes 188 Alloy, 705 °C

Loading Conditions Assumed:

0 - HCF Frequency 1000 Hz
0 - Mission Duration 500 sec
0 - HCF Life N_2 = 50,000,000 Cycles to Failure
0 - LCF Life N_1 = 500 Cycles to Failure

Mission consists of n_1 = 1 LCF Cycle
n_2 = 500,000 HCF Cycles

docProbabWorkshp2001grib%0701

LINEAR DAMAGE RULE (LDR)
PREDICTION OF NUMBER OF MISSIONS

$$\Sigma\left[\frac{n_1}{N_1}+\frac{n_2}{N_2}\right]=1.0$$

$$\Sigma\left[\frac{1}{500}+\frac{50,000}{50,000,000}\right]=\Sigma[0.002+0.010]=\Sigma 0.120=1.0$$

$$\frac{1}{0.012}=83$$

83 Number of Missions by LDR

doc:ProbabWorkshp2001gdd0607G1

DOUBLE LINEAR DAMAGE RULE (DLDR) PREDICTION OF NUMBER OF MISSIONS

Two Linear Damage Rules Summed to 1.0, Sequentially, Where:

$$N_I + N_{II} = N_f$$

$$N_I = f(N_f, N_1/N_2)$$

$$N_{II} = N_f - N_I$$

PHASE I ("Initiation") = N_I:

$$\Sigma\left[\frac{n_1}{N_{I,1}} + \frac{n_2}{N_{I,2}}\right] = 1.0$$

Then,

PHASE II ("Propagation") = N_{II}:

$$\Sigma\left[\frac{n_1}{N_{II,1}} + \frac{n_2}{N_{II,2}}\right] = 1.0$$

Failure Occurs once Phase II reaches 1.0

doc:ProbabWorkshp2001gri00701

Based on DLDR for Haynes 188 at 705 °C:

$$
\begin{array}{llll}
N_{I,1} = & 10 & N_{I,2} = & 48{,}200{,}000 \\
N_{II,1} = & 490 & N_{II,2} = & 1{,}800{,}000 \\
\hline
N_1 = & 500 & N_2 = & 50{,}000{,}000
\end{array}
$$

<u>PHASE I ("Initiation")</u> $= N_I$:

$$\Sigma\left[\frac{n_1}{N_{I,1}}+\frac{n_2}{N_{I,2}}\right]=1.0 \;\;=\;\; \Sigma\left[\frac{1}{10}+\frac{500{,}000}{48{,}200{,}000}\right]=\Sigma[0.1+0.013=0.113]=1.0$$

$$\frac{1}{0.113}= \;\; \textbf{8.8 Missions to "Initiate"}$$

Then,

<u>PHASE II ("Propagation")</u> $= N_{II}$:

$$\Sigma\left[\frac{n_1}{N_{II,1}}+\frac{n_2}{N_{II,2}}\right]=1.0 \;\;=\;\; \Sigma\left[\frac{1}{490}+\frac{500{,}000}{1{,}800{,}000}\right]=\Sigma[0.002+0.278=0.28=1.0]=1.0$$

$$\frac{1}{0.28}= \;\; \textbf{3.6 Missions to "Propagate"}$$

$$8.8+3.6=12.4$$

≈ 12 Missions to Failure by DLDR vs. 83 Missions by LDR

dr:ProbabWorkshp2001gdd060701

EFFECT ON MISSION LIFE
OF IMPROVING FATIGUE RESISTANCE

Improvement	LDR (% increase)	DLDR (% increase)
Baseline Fatigue Curve	83 (--)	12 (--)
Increase LCF by X2	91 (10%)	23 (90%)
Increase HCF by X10	333 (300%)	25 (100%)
Increase HCF by X100	476 (475%)	97 (700%)
Increase LCF by X2 & HCF by X10	500 (500%)	37 (200%)

doc:Probab\Workshp2001grh060701

PSRPLIFE

EXAMPLE APPLICATIONS

0 - StrainRange Partitioning (SRP)
  - Compared to Linear Time- and Cycle Life Fraction Rule

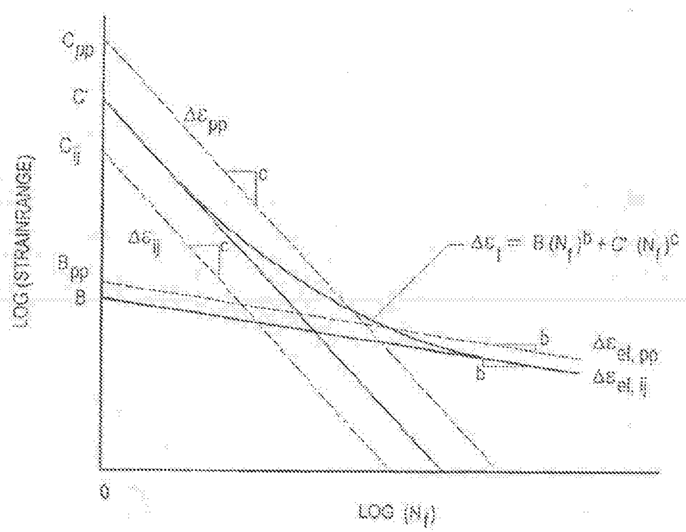
0 - Schematic of Total Strain Version of StrainRange Partitioning (TS-SRP)

0 - Isothermal Total Strain Version of StrainRange Partitioning (TS-SRP)
  - Applied to Inconel 718 at 650 °C

0 - Thermomechanical Fatigue Version of TS-SRP
  - Applied to Haynes 188 & B-1900
  - Applied to Automotive Exhaust System Alloy (Ferritic 409 SS)

docProbabWorkshp2001grb060701

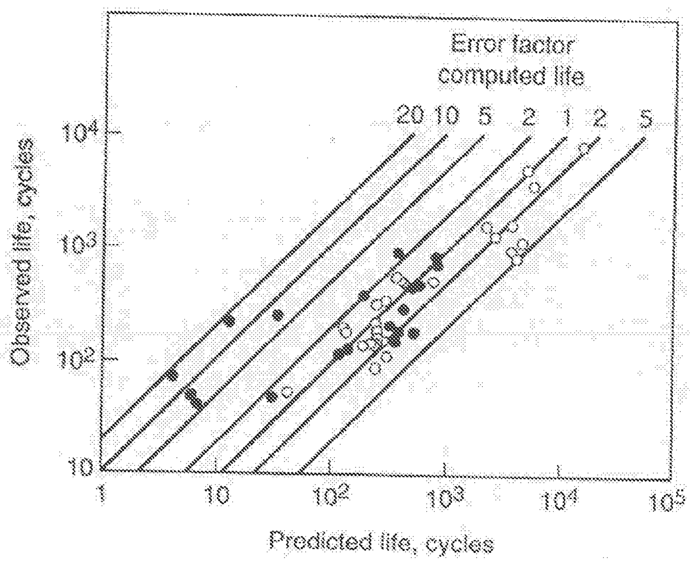
Schematic of Total Strain Version of StrainRange Partitioning (TS-SRP)



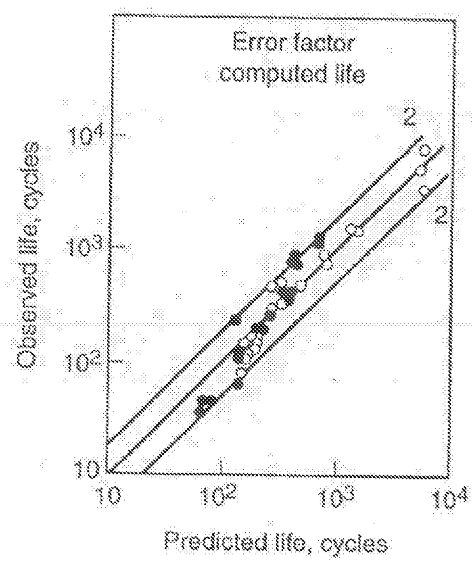
StrainRange Partitioning (SRP)

Prediction Capability Compared to Linear Time- and Cycle Life Fraction Rule

Creep-Fatigue Data for Incoloy 800 & 304 SS



Using predicted time and cycle fractions



Using strain range partitioning

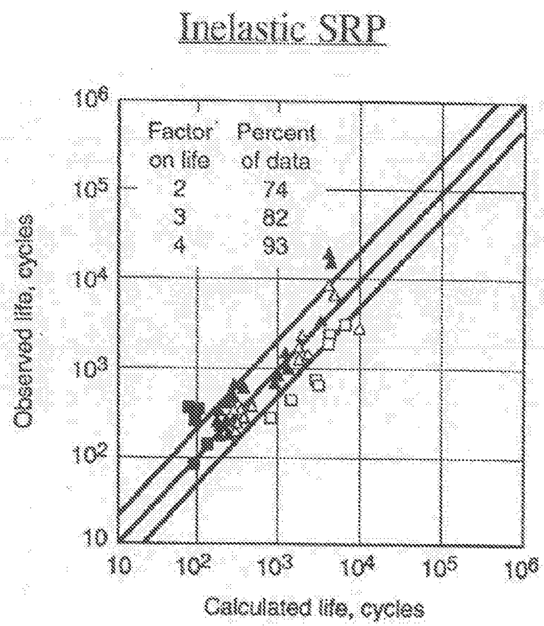
d:x:ProbabWorkshp2001grh060701

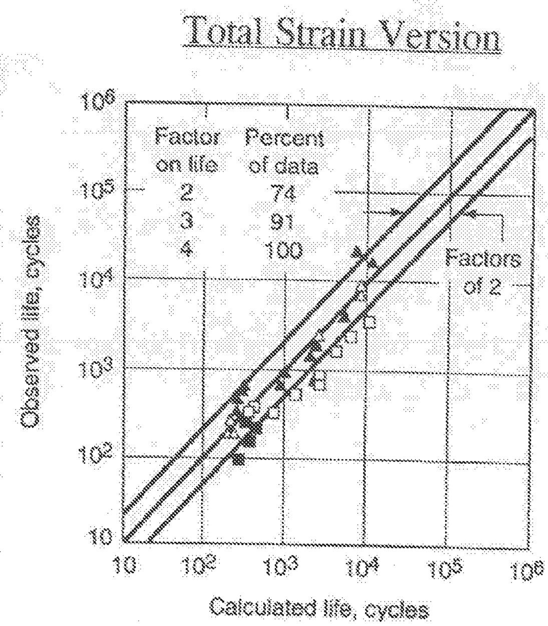
NASA/CP—2002-211682

StrainRange Partitioning (SRP)

Isothermal Total Strain Version of StrainRange Partitioning (TS-SRP)

Predictability of Creep-Fatigue Data for Inconel 718 at 650 °C



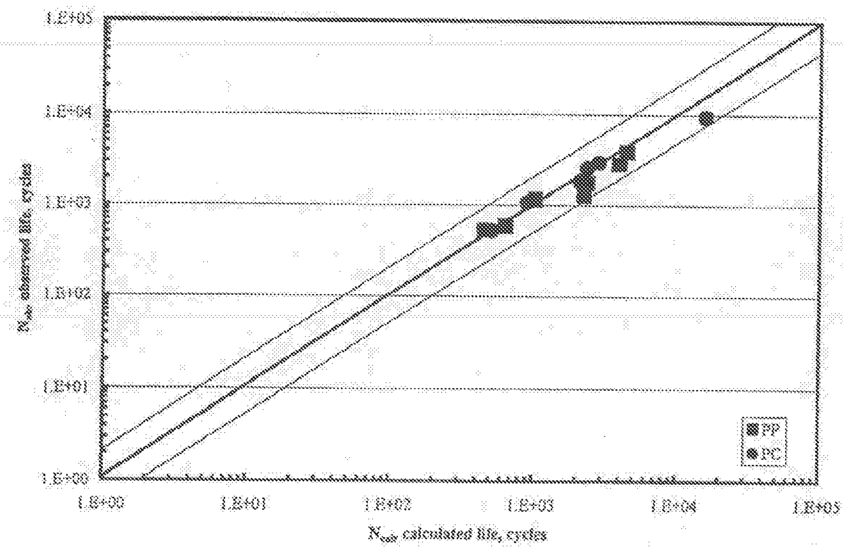


docProbabWorkshp2001gdn00701

StrainRange Partitioning (SRP)

Thermomechanical Fatigue Version of SRP (TMF-SRP) Applied to Automotive Exhaust System Alloy (Ferritic 409 SS)

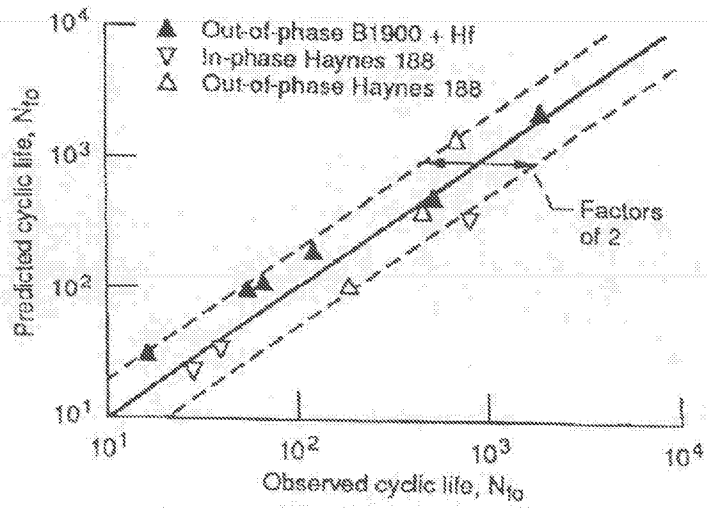
Correlation of calculated and observed lives of bithermal out-of-phase fatigue between 400 and 800 C



docProbabWorkshp2001grh060701

StrainRange Partitioning (SRP)

Thermomechanical Fatigue Version of SRP (TMF-SRP) Applied to Haynes 188 & B-1900



dxcProbabWorkshp2001grs00701