Aerospace Structural Metals Handbook

ALLOY NASA-HR-1

Nickel Base Alloys – Ni

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1 General

NASA-HR-1 is a high-strength Fe-Ni-base superalloy that resists high-pressure hydrogen environment embrittlement (HEE), oxidation, and corrosion. Originally derived from JBK-75, NASA-HR-1 has exceptional HEE resistance that can be attributed to its γ matrix and η-free (Ni_3Ti) grain boundaries. The chemistry was formulated using a design approach capable of accounting for the simultaneous effects of several alloy additions. This approach included (1) systematically modifying γ-matrix compositions based on JBK-75, (2) increasing γ' ($Ni_3(Al,Ti)$) volume fraction and adding γ-matrix strengthening elements to obtain higher strength, and (3) obtaining precipitate-free grain boundaries.

The most outstanding attribute of NASA-HR-1 is its ability to resist HEE while showing much improved strength. NASA-HR-1 has approximately 25% higher yield strength than JBK-75 and exhibits tensile elongation of more than 20% with no ductility loss in a hydrogen environment at 5 ksi, an achievement unparalleled by any other commercially available alloy. Its Cr and Ni contents provide exceptional resistance to environments that promote oxidation and corrosion. Microstructural stability was maintained by improved solid solubility of the γ-matrix, along with the addition of alloying elements to retard η (Ni_3Ti) precipitation. NASA-HR-1 represents a new system that greatly extends the compositional ranges of existing HEE-resistant Fe-Ni-base superalloys.

1.1 Commercial Designation

NASA-HR-1

1.2 Other Designations

None

1.3 Specifications

None

1.3.1 *[Table]* Suggested AMS and ASTM Specifications (Ref. 1,2) for wrought NASA-HR-1.

1.4 Composition

1.4.1 *[Table]* NASA-HR-1 specified composition of cast ingots from primary supplier.

1.5 Heat Treatment and Microstructure

General: NASA-HR-1 is normally processed in a solution-annealed and aged condition in order to properly distribute the strengthening γ' ($Ni_3(Al,Ti)$) precipitate (Refs. 3–4). The ingot must be homogenized at 2100 F and then hot-rolled into plates in the range of 1700 to 2000 F. Heat treatment begins with solutionizing at 1750 F for 1 hour (resulting in large grain size for good creep-rupture resistance) followed by aging at 1325 F for 16 hours (which provides near-maximum hardening).

1.6 Hardness

Solution-treated NASA-HR-1 was used to study the effects of thermal aging at 1335 F from 0.5 to 300 hours. This material had a maximum hardness value of 39 HRC, approximately 5 points higher than A286. NASA-HR-1 has a relatively slower aging response than A286. During aging, A286 reached maximum hardness within 8 to 16 hours, while NASA-HR-1 required 32 hours. NASA-HR-1 retained the same hardness level for up to 160 hours followed by a slight drop to 37.8 HRC after 300 hours.

1.6.1 *[Figure]* Effects of thermal aging on hardness of solution-annealed NASA-HR-1 and A286.

1.7 Forms and Conditions Available

NASA-HR-1 is a wrought superalloy that can be hot- or cold-rolled into billets of various diameters. It should be available as sheet, strip, plate, bar, wire, forgings, seamless tubing, and extrusions in the same commercial range of sizes as A286.

1.8 Melting and Casting Practice

Standard melting practice is to combine vacuum induction melting (VIM) and vacuum arc remelting (VAR) in order to minimize alloying element oxidation and reduce inclusions. The combination of VIM + VAR melting improves homogeneity and results in a decreased scatter of mechanical properties. Satisfactory crucible materials include well-cured alumina or zirconia.

1.9 Hydrogen Embrittlement Resistance

HEE refers to the loss of notched tensile strength or tensile ductility in an alloy, due to the presence of hydrogen. It is usually reported as loss of ductility (elongation %) in a hydrogen atmosphere. Internal hydrogen embrittlement (IHE) refers to loss of ductility when a tensile test bar is exposed to gaseous hydrogen (GH_2) for a long period of time or through electrochemical hydrogen charging. When HEE tests were conducted on NASA-HR-1 in high-pressure hydrogen (5 ksi), its ductility was slightly reduced at 1250 F but little affected at room temperature (Ref. 3).

2 Physical Properties and Environmental Effects

Thermal and other physical properties described are for samples solutionized and heat-treated after being cut from rolled plates. (See Section 1.5.)

2.1 Thermal Properties

2.1.1 Melting Range

Prior to melting, NASA-HR-1 has a homogeneous, single-phase, face-centered cubic structure. Its melting range is 2426 to 2579 F.

2.1.2 Phase Changes

NASA-HR-1 is a γ' ($Ni_3(Al,Ti)$) strengthened superalloy similar to other Fe-Ni-base superalloys. The matrix phase (gamma) is a solid solution of Fe, Ni, Co, and Cr, whereas the precipitate phase (gamma prime) is composed of hardening elements Ti and Al. Another phase has also been observed in the microstructure. The eta-phase (η), which is a Ti-rich acicular precipitate (Ni_3Ti), generally forms at the grain boundaries under certain heat-treated conditions, and forms within the grains after prolonged exposure to elevated temperatures. When properly heat treated, NASA-HR-1 displays a very clean microstructure in the wrought condition, with none of the grain boundary η precipitate generally present in Fe-Ni-base alloys with high Ti content.

The clean grain boundary observed in NASA-HR-1 could be partly attributed to the addition of W, which has been reported to retard the reaction of the metastable γ' phase ($Ni_3(Al,Ti)$) to stable η (Ni_3Ti) in some Ni-base superalloys (Ref. 5). This retardation could be caused by either a decreased diffusion rate of the Ti atoms to grain boundaries or by an increased energy of formation of stacking faults.

2.1.3 Thermal Conductivity

2.1.3.1 *[Figure]* Thermal conductivity as a function of temperature for wrought NASA-HR-1.

2.1.4 Thermal Expansion

2.1.4.1 *[Figure]* Thermal expansion as a function of temperature for wrought NASA-HR-1.

2.1.5 Specific Heat

2.1.5.1 *[Figure]* Specific heat as a function of temperature for wrought NASA-HR-1.

2.1.6 Thermal Diffusivity

2.1.6.1 *[Figure]* Thermal diffusivity as a function of temperature for wrought NASA-HR-1.

2.2 Other Physical Properties

2.2.1 Density is 8.07 g/cc or 0.292 lb/in^3 at room temperature.

2.2.2 Electrical Properties

2.2.3 Magnetic Properties

NASA-HR-1 is weakly paramagnetic at room temperature.

2.2.4 Emittance

2.2.5 Damping Capacity

2.3 Chemical Environments

General and stress corrosion.

General. NASA-HR-1 contains Ni and Cr, which provide excellent corrosion resistance. Since NASA-HR-1 has a composition similar to A286 and JBK-75, it should have excellent resistance to stress corrosion in aqueous NaCl at room temperature but be susceptible to stress corrosion in boiling NaCl.

2.4 Nuclear Properties

2.5 Hydrogen Embrittlement

General. NASA-HR-1 was designed for hydrogen resistance (Ref. 3). When it is exposed to hydrogen gas, atomic hydrogen enters the matrix and interacts with the dislocations. Hydrogen embrittlement arises from the degree of this interaction and the reduction in mobility of dislocations providing ductility that results. The ductility of NASA-HR-1 is little affected by testing in a high-pressure hydrogen atmosphere. Various mechanical properties have been evaluated by testing NASA-HR-1 in both high-pressure hydrogen and helium (or air) to provide practical data concerning hydrogen resistance.

2.6 Oxygen Embrittlement

General. NASA-HR-1 contains a significant amount of Cr, which provides oxidation resistance comparable to A286 and JBK-75.

3 Mechanical Properties

3.1 Specified Mechanical Properties

3.2 Mechanical Properties at Room Temperature

3.2.1 Tension stress-strain diagrams and tensile properties.

3.2.2 Compression stress-strain diagrams and compression properties.

3.2.3 Impact.

3.2.4 Bending.

3.2.5 Torsion and shear.

3.2.6 Bearing.

3.2.7 Stress concentration.

3.2.7.1 Notch properties.

3.2.7.2 Fracture toughness.

3.3 Mechanical Properties at Various Temperatures

3.3.1 Tensile properties.

Typical tensile properties are reported here for thermo-mechanically processed (wrought) NASA-HR-1. As temperatures increase to 1200 F, the tensile strength of NASA-HR-1 slowly drops. As temperatures increase above 1200 F, properties drop significantly.

3.3.1.1 *[Figure]* Temperature dependence of tensile properties of wrought NASA-HR-1.

3.3.1.2 *[Table]* Typical properties of wrought and heat-treated NASA-HR-1 in air and high-pressure hydrogen (5 ksi) at room temperature (Ref. 3).

3.3.1.3 *[Table]* Typical properties of wrought and heat-treated alloys similar to NASA-HR-1 in high-pressure helium and hydrogen (5 ksi) at 1250 F (Ref. 3).

3.3.1.4 *[Table]* Typical strength and ductility of NASA-HR-1 and two similar alloys of comparable strength in wrought and cast conditions at room temperature.

3.3.2 Compression stress-strain diagrams and compression properties.

3.3.3 Impact.

3.3.4 Bending.

3.3.5 Torsion and shear.

3.3.6 Bearing.

3.3.7 Stress concentration.

3.3.7.1 Notch properties.
3.3.7.2 Fracture toughness.

3.3.8 Combined loading.

3.4 Creep and Creep-Rupture Properties

3.4.1 *[Figure]* Creep-rupture properties of wrought NASA-HR-1 in heat-treated condition.

3.5 Fatigue Properties

NASA-HR-1 has excellent fatigue resistance in air and high-pressure hydrogen at room and elevated temperatures.

3.5.1 Conventional high cycle fatigue.

3.5.2 Low cycle fatigue.

3.5.2.1 *[Figure]* Low cycle fatigue life of wrought NASA-HR-1 in high-pressure hydrogen and helium (5 ksi) at room temperature.

3.5.2.2 *[Figure]* Temperature effects on low cycle fatigue life of wrought NASA-HR-1 in high-pressure hydrogen (5 ksi) at room temperature and 1250 F.

3.6 Elastic Properties

3.6.1 Poisson's ratio.

3.6.2 Young's modulus at room temperature – 29.5 x 10^6 psi or 204 GPa.

3.6.3 Modulus of rigidity.

3.6.4 Tangent modulus.

3.6.5 Secant modulus.

4 Fabrication

NASA-HR-1 can be easily cast using vacuum induction melting. Recommended casting temperature range is 2600 to 2700 F. Air melting is possible, but will lead to loss of alloying elements with property degradation.

NASA-HR-1 ingots can be easily formed, machined, and welded using conventional procedures for Fe-Ni base superalloys. Deformation and thermo-mechanical processes are easy to perform, due to low hardener contents. Studies indicate that NASA-HR-1 is readily weldable (Ref. 3).

Fine grain microstructure can be obtained by hot-rolling in the temperature range of 1800 to 2000 F. NASA-HR-1 can also be cold-rolled at room temperature to 60% reduction, with no signs of cracking. When cold-rolled and aged, NASA-HR-1 exhibits hardnesses over 50 HRC.

4.1 Forming

In general, the formability of NASA-HR-1 plate in the annealed condition is similar to that of other Fe-Ni-based superalloys, such as A286 and JBK-75.

4.1.1 Forging characteristics are similar to those of A286 and JBK-75.

4.1.2 NASA-HR-1 has good ductility at elevated temperatures, which facilitates hot working. Forging characteristics are similar to those of A286 and JBK-75.

4.2 Machining and Grinding

NASA-HR-1 does not machine well in the solution-treated condition. However, it can be easily machined in the fully heat-treated condition after being hardened.

4.3 Joining

NASA-HR-1 is weldable, preferably in the solution-treated condition. Varestraint weld test results indicated that NASA-HR-1 has weldability superior to that of IN-718.

4.3.1 *[Figure]* Varestraint weld test results for NASA-HR-1 and IN-718.

4.4 Surface Treating

References

1. AMS Specifications, Society of Automotive Engineers, 400 Commonwealth Drive, Warrendale, PA 15096.
2. ASTM Specifications, American Society for Testing and Materials, 1916 Race Street, Philadelphia, PA 19103.
3. P.S. Chen, B. Panda, and B.N. Bhat: "NASA-HR-1, A New Hydrogen-Resistant Fe-Ni-Base Superalloy," *Hydrogen Effects in Materials,* edited by A.W. Thompson and N.R. Moody, Minerals, Metals, and Materials Society, 1996.
4. P.S. Chen: "Optimization of A Potential Hydrogen Resistant Composition," Report No. IITRI-P06150-P513, NASA Contract NAS8-38258, 1993. Available from the Central Document Repository, George C. Marshall Space Flight Center, Huntsville, AL.
5. A. Havalda: "Influence of Tungsten on the γ' to η Transformation and Carbide Reactions in Nickel-Base Superalloys," *Trans. ASM,* Vol. 62, 1969, pp. 581-89.

Table 1.3.1 Suggested AMS and ASTM Specifications for wrought NASA-HR-1 (Refs. 1–2)

Specification	Description
AMS 2261	Tolerances, nickel, nickel alloys, and cobalt alloys, bars and forging stock
AMS 2262	Tolerances, nickel, nickel alloys, and cobalt alloys, sheet, strip and plate
AMS 2269	Chemical check analysis limits, wrought nickel alloys and cobalt alloys
AMS 2350	Standards and test methods
AMS 2806	Identification of bars, wire, mechanical tubing and extrusions, carbon and alloy steels, and corrosion and heat resistant steels and alloys
AMS 2808	Identification, forgings
ASTM E8	Tension testing of metallic materials
ASTM E112	Determining average grain size
ASTM E139	Conducting creep, creep rupture, and stress rupture tests of metallic materials
ASTM E354	Chemical analysis of high temperature, electrical, magnetic, and other similar iron, nickel, and cobalt alloys

Table 1.4.1 NASA-HR-1 specified composition of cast ingots from primary supplier (wt %)

Element	Range
Al	0.2 – 0.3%
C	0.01% (maximum)
Cr	14 – 16%
Co	3.0 – 3.5%
Fe	29 – 33%
Ni	33 – 35%
Ti	2.5 – 2.7%
Mo	1.8 – 2.2%
Si	0.05% (maximum)
W	1.5 – 2.0%
V	0.3 – 0.5%
S	0.005% (maximum)
P	0.005% (maximum)
O, N	0.002% (maximum)

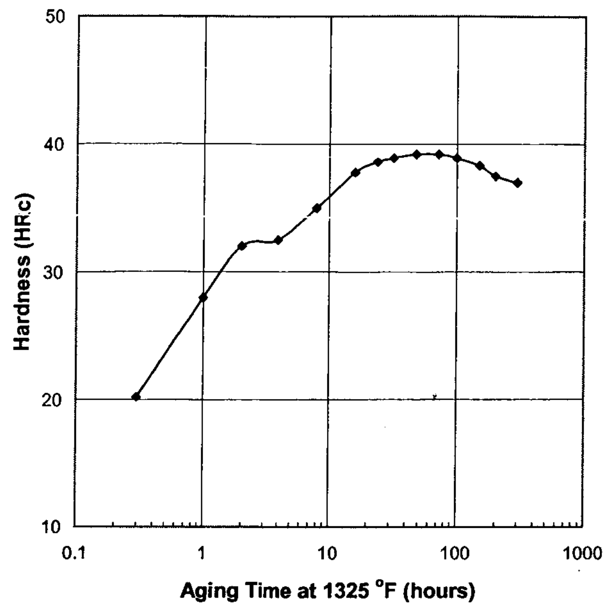

Figure 1.6.1 Effects of thermal aging on hardness of solution-annealed NASA-HR-1 and A286 (Ref. 3)

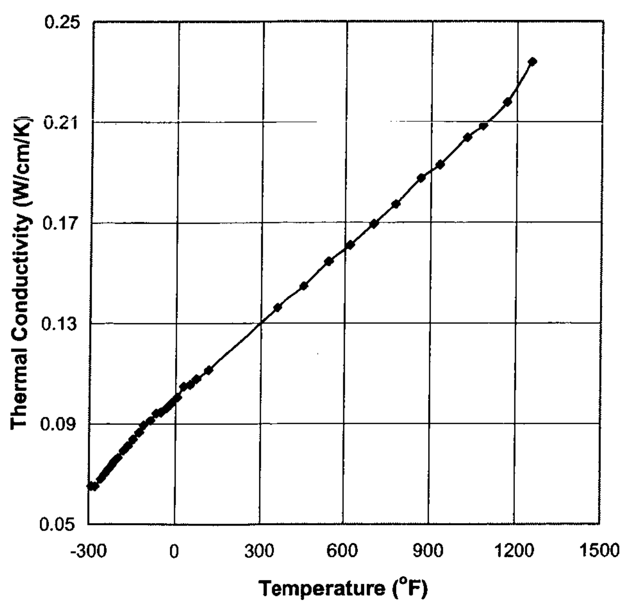

Figure 2.1.3.1 Thermal conductivity as a function of temperature for wrought NASA-HR-1

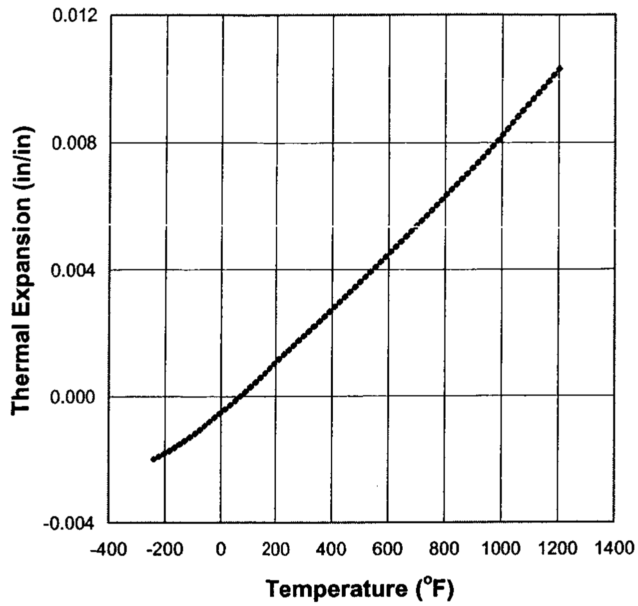

Figure 2.1.4.1 Thermal expansion as a function of temperature for wrought NASA-HR-1

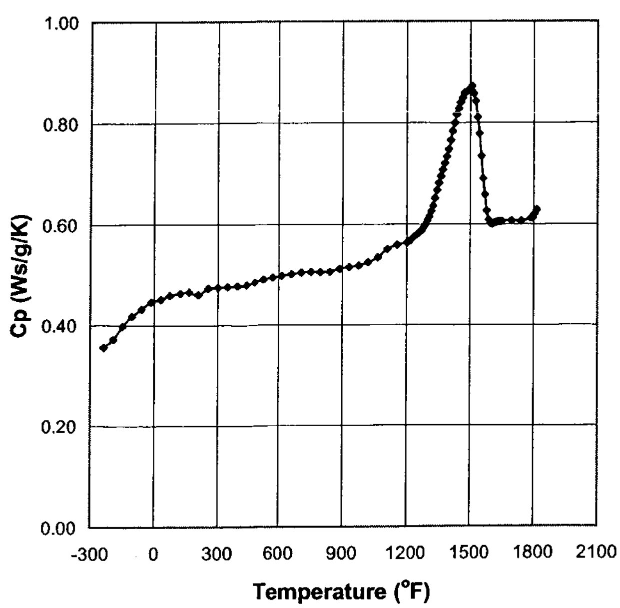

Figure 2.1.5.1 Specific heat as a function of temperature for wrought NASA-HR-1

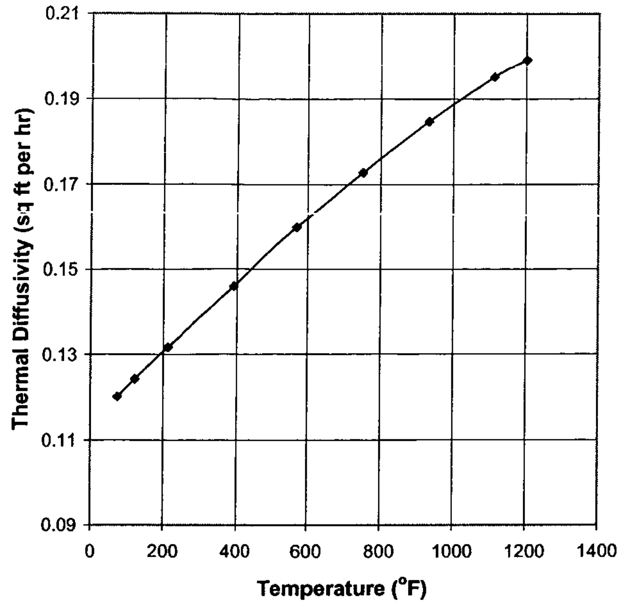

Figure 2.1.6.1 Thermal diffusivity as a function of temperature for wrought NASA-HR-1

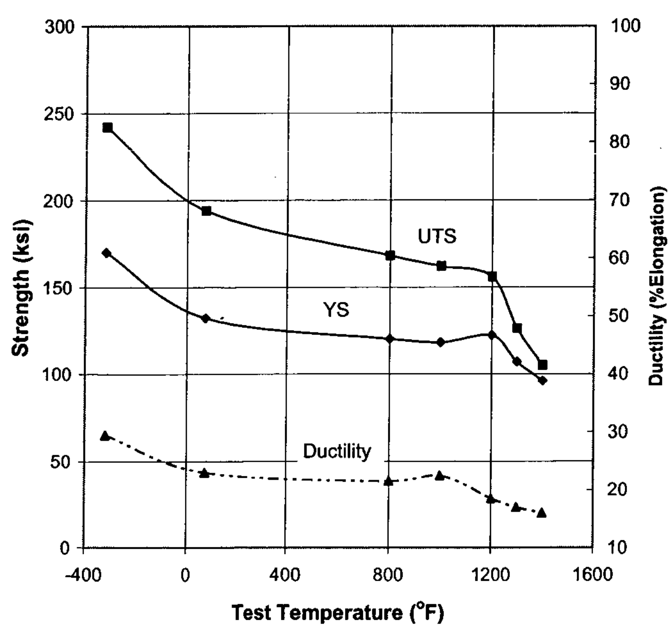

Figure 3.3.1.1 Temperature dependence of tensile properties of wrought NASA-HR-1

Table 3.3.1.2 Typical properties of wrought and heat-treated NASA-HR-1 in air and high-pressure hydrogen (5 ksi) at room temperature

Environment	Yield Strength (ksi)	Ultimate Tensile Strength (ksi)	Elongation (%)	Reduction in Area (%)
Air	136.9	182.8	23.6	34.0
5-ksi GH_2	128.9	175.3	23.4	34.7

Table 3.3.1.3 Typical properties of wrought and heat-treated alloys similar to NASA-HR-1 in high-pressure helium and hydrogen (5 ksi) at 1250 F

Environment	Yield Strength (ksi)	Ultimate Tensile Strength (ksi)	Elongation (%)	Reduction in Area (%)
5-ksi GHe	114.4	126.2	22.6	33.1
5-ksi GH_2	114.0	128.8	19.4	25.6

Table 3.3.1.4 Typical strength and ductility of NASA-HR-1 and two similar alloys of comparable strength in wrought and cast conditions at room temperature

ALLOY	WROUGHT/THERMO-MECHANICALLY PROCESSED		
	Yield Strength (ksi)	Ultimate Tensile Strength (ksi)	Elongation (%)
NASA-HR-1	137	183	24
A286	104	157	25
JBK-75	108	164	27

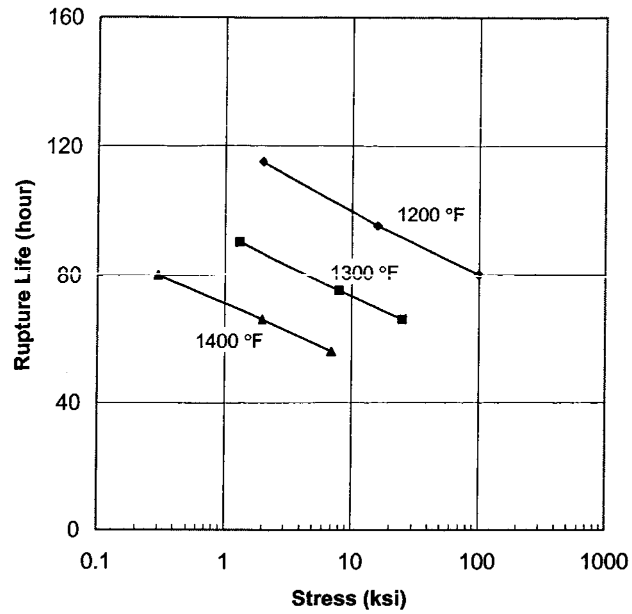

Figure 3.4.1 Creep-rupture properties of wrought NASA-HR-1 in heat-treated condition

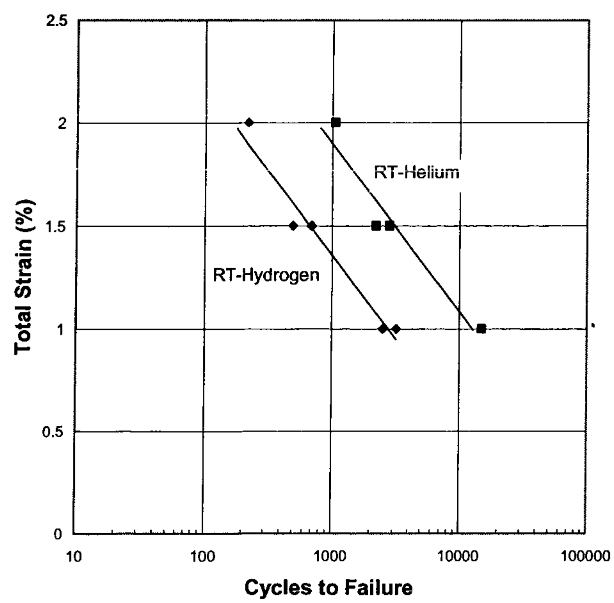

Figure 3.5.2.1 Low cycle fatigue life of wrought NASA-HR-1 in high-pressure hydrogen and helium (5 ksi) at room temperature

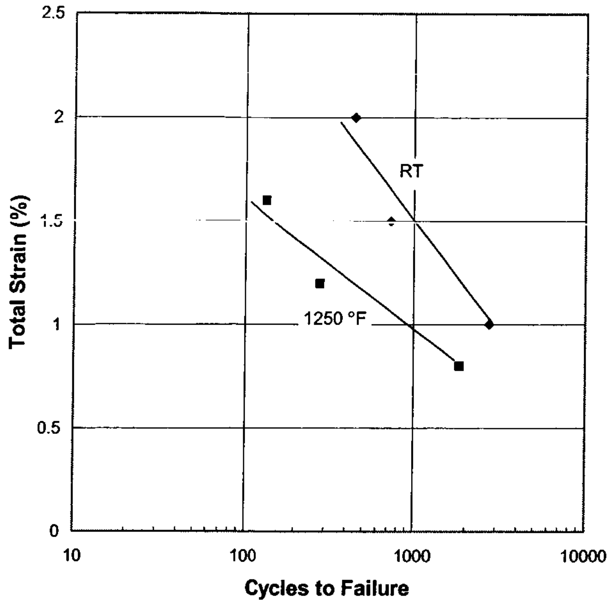

Figure 3.5.2.2 Temperature effects on low cycle fatigue life of wrought NASA-HR-1 in high-pressure hydrogen (5 ksi) at room temperature and 1250 F

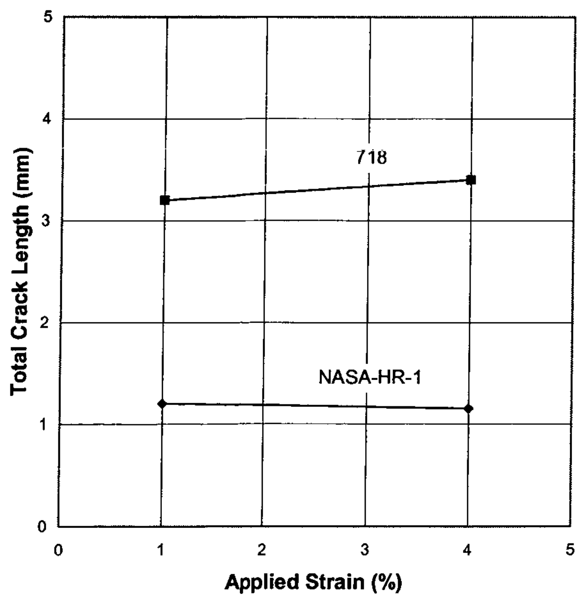

Figure 4.3.1 Varestraint test results for NASA-HR-1 and IN-718