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The Influence of Advanced Processing on PWA 1480

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Single crystal nickel base superalloys have been evaluated for potential application in the Space Shuttle Main Engine (SSME) high pressure turbopump turbines. Single crystals exhibit low cycle and high cycle fatigue life improvements over directionally solidified, hafnium modified, MAR-M246 (DS MAR-M246), the current SSME turbine blade alloy. The extreme start and stop thermal transients, high rotational speeds and high frequency vibrational modes dictate that these properties are life limiting in the SSME. In contrast, the long time creep and stress rupture behavior in gas turbine engines, for which the turbine blade alloys were developed, are not of concern for the SSME application. Although the fatigue life improvements due to a direct material substitution are significant, additional gains are possible through the application of advanced processing techniques to the single crystal production sequence. The primary initiation sites for fracture in single crystal superalloys, especially under cyclic loads, are internal casting pores. This casting porosity is inherent due to the dendritic solidification of these two phase systems. Pores are caused by shrinkage of the interdendritic liquid during final solidification. The primary objective of this program was to evaluate the potential improvements in microstructures and material properties due to the reduction in size and density of these casting defects due to the application of high thermal gradient casting and hot isostatic pressing.

PWA 1480 was chosen as the alloy to be evaluated for this program. The alloy had previously been chosen for the SSME application after screening of the commercially available single crystal alloys. PWA 1480 exhibited superior hydrogen environment embrittlement resistance relative to other candidate single crystal superalloys. In addition, a significant data base of material properties had been compiled for this alloy. Baseline tests for this program were conducted on standard commercial thermal gradient cast and standard PWA 1480 heat treated material. High thermal gradient casting was evaluated as an avenue for reducing the size of casting porosity. Hot isostatic pressing (HIP) was also employed for the elimination of casting pores. An alternate to the standard PWA 1480 coating plus diffusion bonding aging heat treatment cycle was also evaluated for potential improvements in the properties of interest to the SSME application. Microstructural changes associated with the high thermal gradient casting process were quantified by measurement of the size and density of the casting porosity, amount of retained casting eutectic and dendrite arm spacings. Tensile tests were conducted in air at 760°C. Stress rupture tests were conducted in air at 871°C at an initial applied stress of 620 MPa. Statistically determined numbers of low cycle and high cycle fatigue tests were conducted, for each material condition, to quantify changes in life due to process improvements. Three low cycle fatigue tests were conducted at 538°C and 2.0% total strain range and eight high cycle fatigue tests were conducted at room temperature and at 871°C, at a stress ratio of 0.47.

High thermal gradient casting was found to reduce both the size and density of the internal casting porosity relative to the standard thermal gradient process. The smaller pore size is a result of the decreased dendrite arm spacing afforded by the higher casting thermal gradient. Elemental segregation between the dendritic and interdendritic regions is also reduced. The reduced pore size provided an increase in both low cycle and high cycle fatigue lives relative to the standard gradient material. In addition, the high thermal gradient material exhibited a superior combination of tensile strength and ductility, though with a reduction in short time stress rupture life. These results are complicated somewhat due to the introduction of the alternate heat treatment schedule along with the high gradient casting process. The high cycle fatigue life improvement should be more sensitive to the initiating flaw (pore) size, while the low cycle fatigue, tensile and stress rupture behaviors are more generally related to the morphology and character of the strengthening gamma prime precipitates.

Test results from the high gradient cast and HIP material were poor due to post-HIP heat treatment problems. HIP of the standard thermal gradient material was followed by the alternate heat treatment cycle. The combination of strength and ductility was improved somewhat, especially at 760°C. Stress rupture life was again found to be reduced relative to the standard process material. Low cycle fatigue life was approximately doubled, by the application of HIP and the alternate heat treatment relative to the baseline material. High cycle fatigue lives were conducted at stress levels different from the baseline material so a direct statistical comparison is difficult. An increase in life is indicated.

The results of the program have shown an improvement in material microstructure due to high thermal gradient casting. Improved homogeneity of PWA 1480 is advantageous in providing an improved solution heat treatment window and, potentially, easier HIP. High thermal gradient casting improves fatigue life by reducing casting pore size. The alternate heat treatment improves the balance of strength and ductility which appears to improve low cycle fatigue life, but with a reduction in short time stress rupture life. Based upon the testing from this program, hot isostatic pressing appears to afford further improvements in cyclic life, though additional evaluation is suggested. Development of the alternate heat treatment is not recommended due to the reduced stress rupture capability and the need to develop a new properties data base. High thermal gradient casting and HIP are recommended for application to single crystal castings.

Improving Properties of Rocket Engine Turbine Blades

Technical Change	Property Benefit
• Substitute single crystal for columnar grained alloy	• Eliminate carbides as fatigue initiation sites
• High gradient single crystal casting	• Improve homogeneity, increase fatigue life
• Hot isostatically pressed single crystal	• Eliminate porosity as fatigue initiation site
• Alternate heat treatment	• Improve hydrogen environment embrittlement resistance
• Crystallographic orientation control	• Improve hydrogen environment embrittlement resistance, control dynamic response
• Rocket engine turbine blade alloy development	• Hydrogen resistant, fatigue capable alloy

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ADVANCED PROCESSING OF PWA 1480
PROGRAM OBJECTIVE

EVALUATE THE INFLUENCE OF HIGH THERMAL GRADIENT CASTING, HOT ISOSTATIC PRESSING AND ALTERNATE HEAT TREATMENT ON THE MICROSTRUCTURE AND MECHANICAL PROPERTIES OF A SINGLE CRYSTAL NICKEL BASE SUPERALLOY

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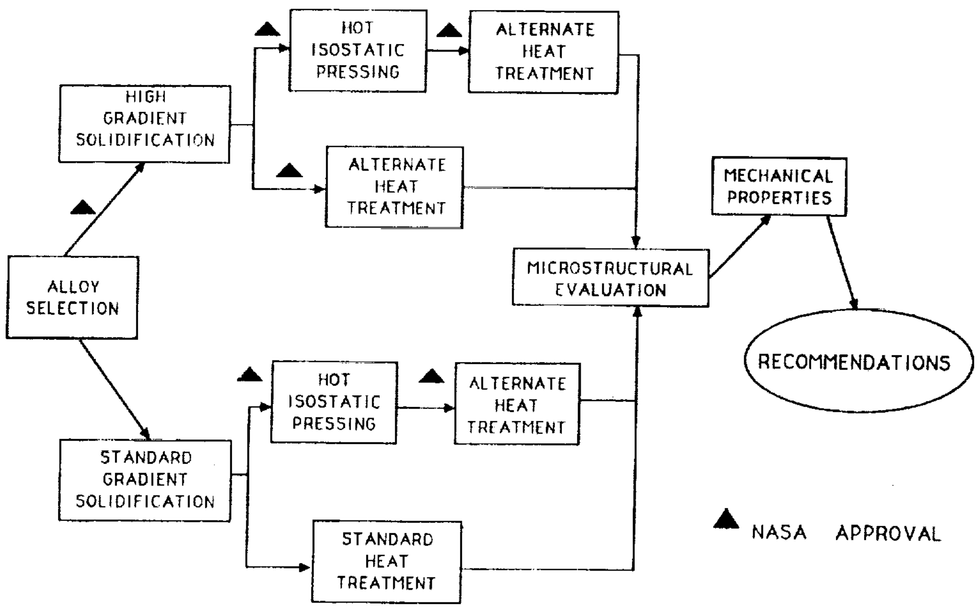
ADVANCED PROCESSING OF PWA 1480
PROGRAM LOGIC



ADVANCED PROCESSING OF PWA 1480
ALLOY SELECTION CRITERIA

- **HYDROGEN ENVIRONMENT EMBRITTLEMENT RESISTANCE SUPERIOR TO DS MAR-M246**
- **EXISTING DATA BASE**
- **PWA 1480 HAD BEEN SELECTED FOR SSME TURBINE BLADE DEVELOPMENT**

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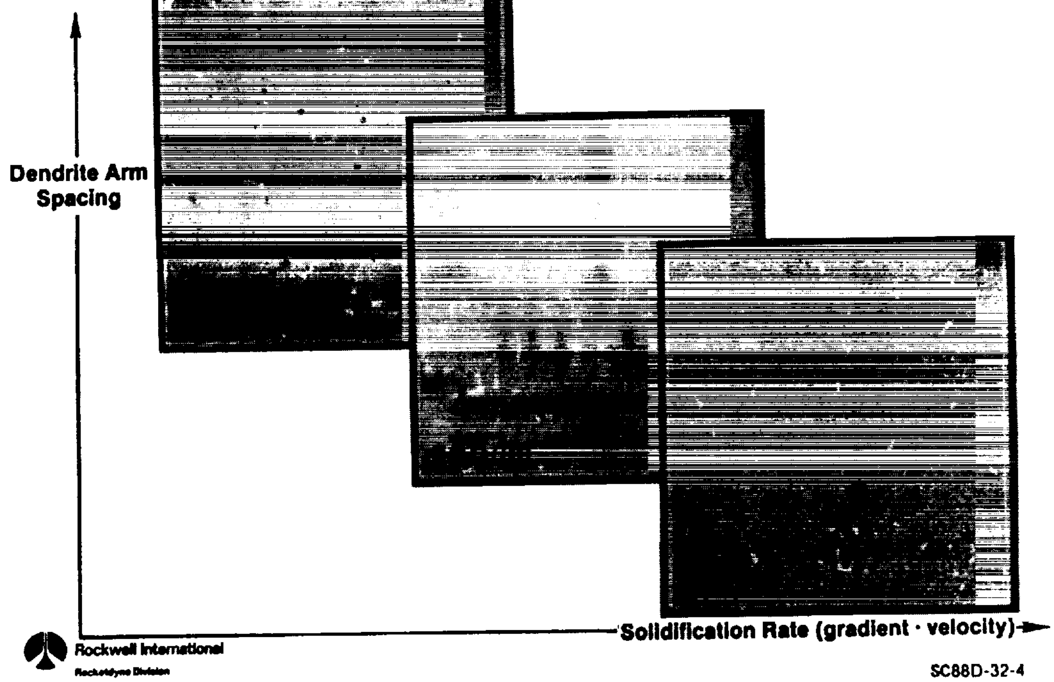
Influence of Casting Process on Microstructure of PWA 1480



ADVANCED PROCESSING OF PWA 1480
CASTING THERMAL GRADIENT

CASTING PROCESS	AVERAGE DAS (MICRONS)	CALCULATED GRADIENT (C/CM)
STANDARD	445	12
HIGH	220	50

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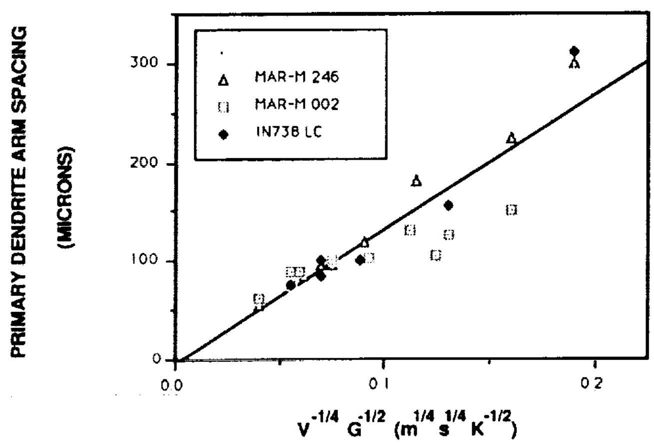
ADVANCED PROCESSING OF PWA 1480
DENDRITE ARM SPACINGS



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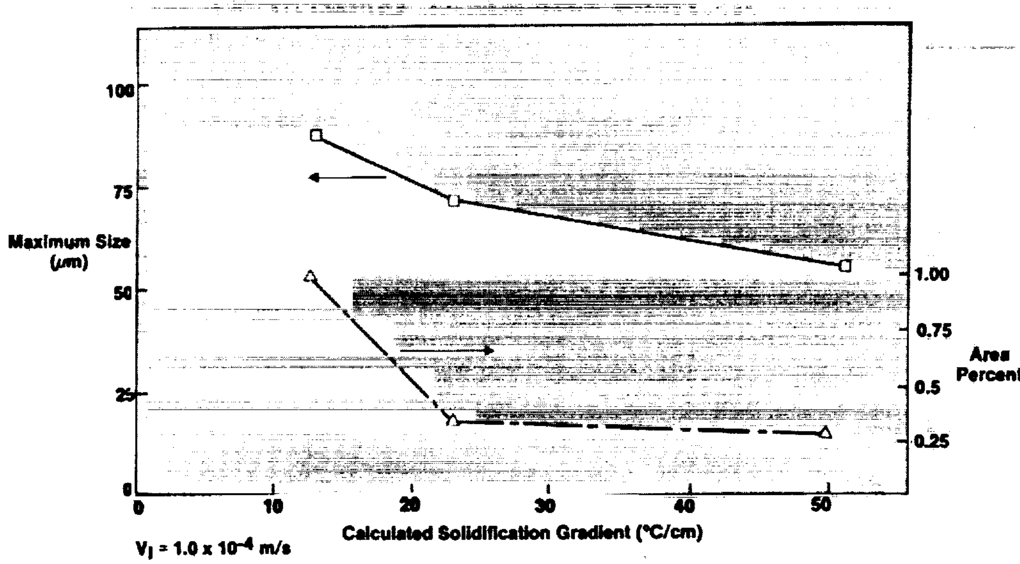
Influence of Thermal Gradient on Size and Distribution of Pores in PWA 1480



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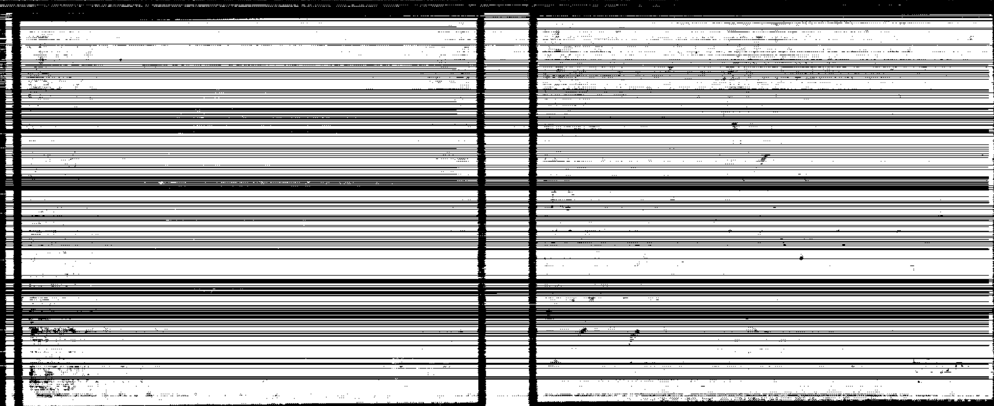
Hot Isostatic Pressing



Internal Recrystallization | Surface Carburization

HIP Cycle = 103.5 MPa/1128°C/4 h

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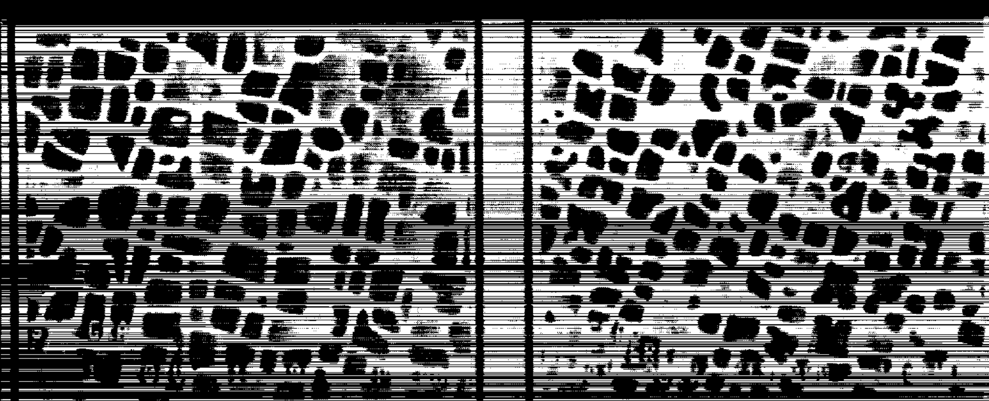
Heat Treated Microstructures



Standard Heat Treatment
Solution Heat Treat
Plus: 1,080°C/ 4 h
Plus: 871°C/32 h

Alternate Heat Treatment
Solution Heat Treat
Plus: 1,010°C/ 2 h
Plus: 871°C/48 h

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ADVANCED PROCESSING OF PWA 1480
AVERAGE TENSILE TEST RESULTS

CASTING GRADIENT	HEAT TREATMENT	TEMPERATURE (C)	YIELD STRENGTH (MPa)	ULTIMATE STRENGTH (MPa)	REDUCTION OF AREA (%)	ELONGATION (%)
STANDARD	STANDARD	24	1024	1075	12.5	11.7
STANDARD	HIP/ALT.	24	989	1219	9.2	9.8
HIGH	ALTERNATE	24	1080	1209	10.3	10.3
HIGH	HIP/ALT.	24	973	1003	3.8	NA
STANDARD	STANDARD	760	1149	1273	7.6	5.0
STANDARD	HIP/ALT.	760	1067	1240	12.9	13.2
HIGH	ALTERNATE	760	1110	1303	12.6	NA
HIGH	HIP/ALT.	760	972	1136	24.8	12.5

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ADVANCED PROCESSING OF PWA 1480
AVERAGE STRESS RUPTURE TEST RESULTS

CASTING GRADIENT	HEAT TREATMENT	TIME TO RUPTURE (HOURS)	ELONGATION (%)
STANDARD	STANDARD	14	NA
STANDARD	HIP/ALT.	4	22
HIGH	ALTERNATE	9.4	15
HIGH	HIP/ALT.	2.8	6.2

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ADVANCED PROCESSING OF PWA 1480
STRESS RUPTURE FRACTOGRAPHY

FRACTURE SURFACE OF NON-HIP, HIGH GRADIENT STRESS RUPTURE BAR. FRACTURE INITIATES AT INTERNAL CASTING POROSITY AT 'A' AND LINKS UP BY DUCTILE TEARING AT 'B'.

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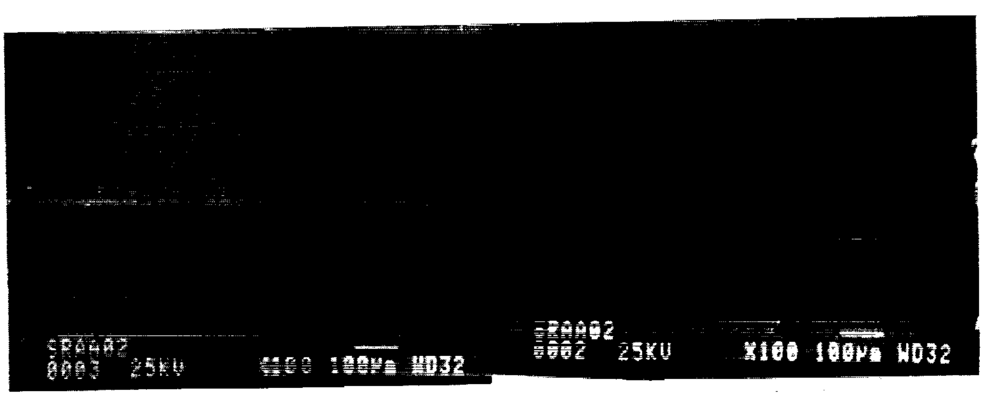
ADVANCED PROCESSING OF PWA 1480
STRESS RUPTURE FRACTOGRAPHY



LONGITUDINAL SECTION THROUGH FAILED STRESS RUPTURE BAR SHOWS CRACK INITIATION AT INTERNAL CASTING POROSITY (ARROWS)

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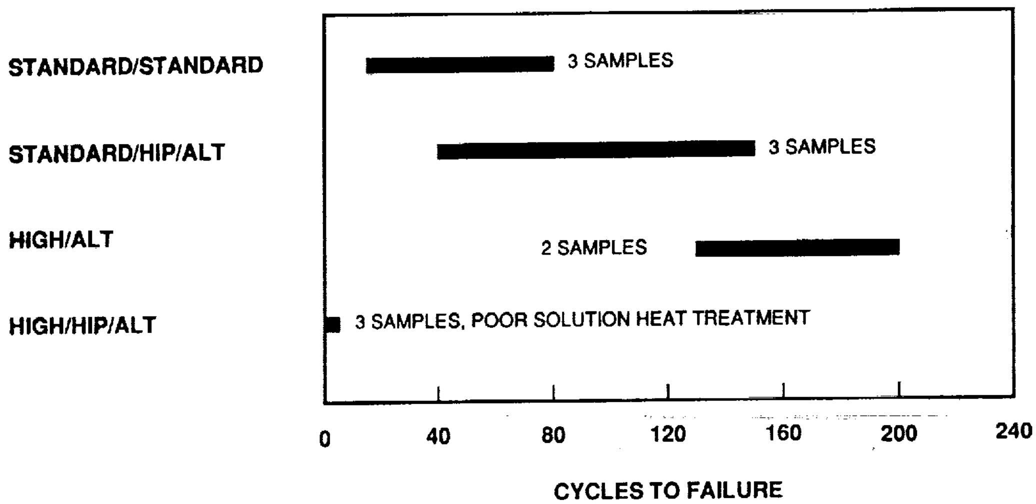
ADVANCED PROCESSING OF PWA 1480
LOW CYCLE FATIGUE TEST RESULTS



538C, 2.0% STRAIN RANGE

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ADVANCED PROCESSING OF PWA 1480
LOW CYCLE FATIGUE FRACTOGRAPHY

CRACK INITIATION IS AT THE SPECIMEN SURFACE OR AT NEAR SURFACE DEFECTS

PROPAGATION IS STAGE I ON {111} TYPE PLANES

R = -1.0, 538C

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ADVANCED PROCESSING OF PWA 1480
HIGH CYCLE FATIGUE TEST RESULTS

(R = 0.47)

CASTING GRADIENT	HEAT TREATMENT	TEMPERATURE (C)	NUMBER OF TESTS	AVERAGE CYCLES TO FAILURE	STANDARD DEVIATION
STANDARD	STANDARD	24	8	58881	42528
STANDARD	HIP/ALT.	24	-	-	- *
HIGH	ALTERNATE	24	4	3.13×10^6	4.6×10^6
HIGH	HIP/ALT.	24	1	4.3 X 10 6	-
STANDARD	STANDARD	871	8	74320	60163
STANDARD	HIP/ALT.	871	-	-	- *
HIGH	ALTERNATE	871	5	1.18 X 106	594000
HIGH	HIP/ALT.	871	6	71246	72817

* TESTED AT DIFFERENT STRESS LEVELS

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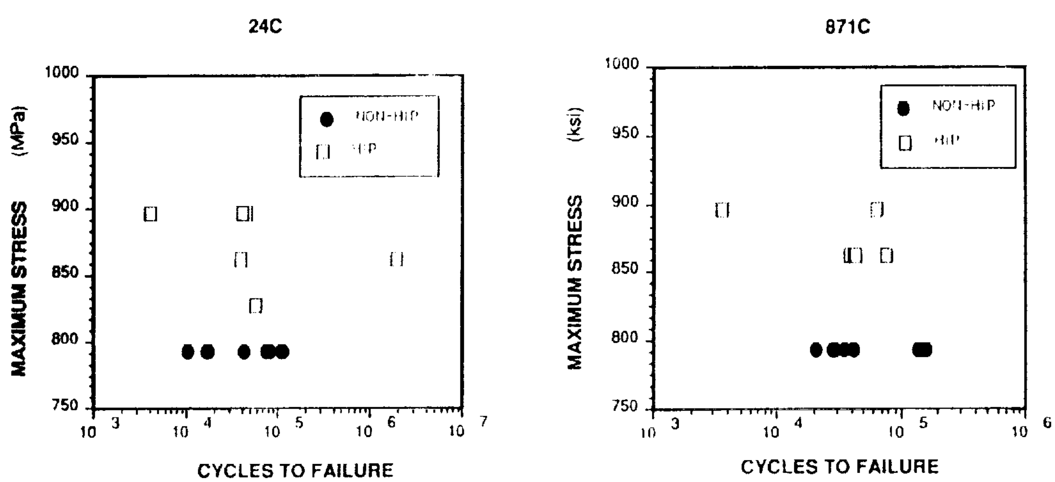
ADVANCED PROCESSING OF PWA 1480
STANDARD GRADIENT HCF RESULTS

R = 0.47



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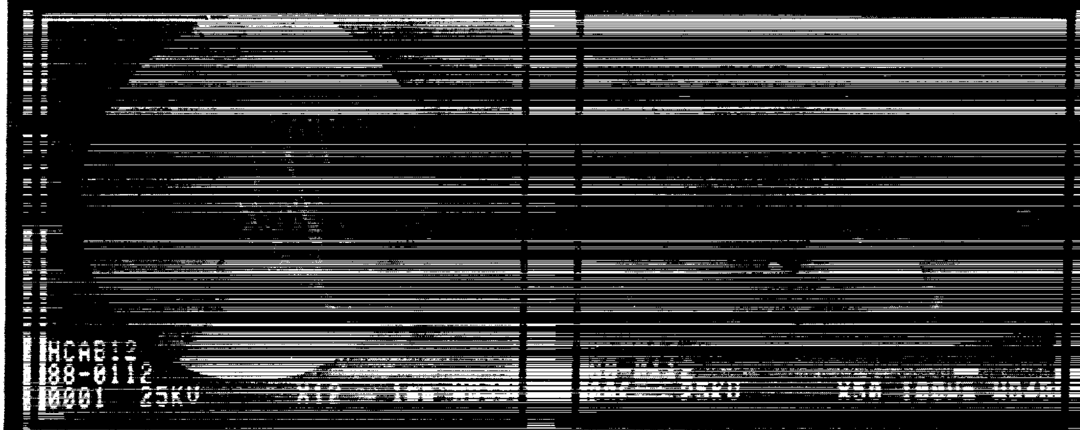
High Cycle Fatigue Failure Analysis

20°C, R = 0.47, Maximum Stress = 793 MPa

$N_f = 7.69 \times 10^{5}$ Cycles



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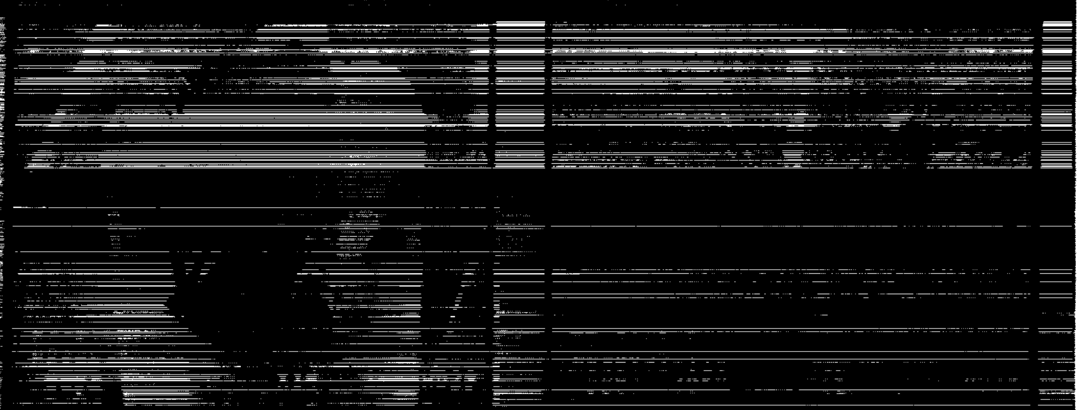
High Cycle Fatigue Failure Analysis

871°C, R = 0.47, Maximum Stress = 793 MPa

$N_f = 9.97 \times 10^{7}$ Cycles



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ADVANCED PROCESSING OF PWA 1480
CONCLUSIONS AND RECOMMENDATIONS

- HIGH THERMAL GRADIENT CASTING
  - PRODUCES LESS SEGREGATED, FINER MICROSTRUCTURE
  - REDUCES PORE SIZE
  - RECOMMENDED FOR POTENTIAL IMPROVED HEAT TREATMENT AND HIP

- HOT ISOSTATIC PRESSING
  - REMOVES INTERNAL CASTING POROSITY
  - SIGNIFICANT CYCLIC LIFE IMPROVEMENT
  - RECOMMENDED FOR APPLICATIONS INVOLVING FATIGUE LIMITED LIFE

- ALTERNATE HEAT TREATMENT
  - SOME TENSILE PROPERTY IMPROVEMENT
  - BENEFIT IS NOT SIGNIFICANT ENOUGH TO WARRANT APPLICATION

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