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Application of Single Crystal Superalloys for Earth-to-Orbit Propulsion Systems

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R.L. Dreshfield
Lewis Research Center
Cleveland, Ohio

and

R.A. Parr
George C. Marshall Space Flight Center
Marshall Space Flight Center, Alabama

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R.L. Dreshfield
National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135

and

R.A. Parr
National Aeronautics and Space Administration
George C. Marshall Space Flight Center
Marshall Space Flight Center, Alabama 35812

Abstract

Single crystal superalloys were first identified as potentially useful engineering materials for aircraft gas turbine engines in the mid-1960's. Although they were not introduced into service as turbine blades in commercial aircraft engines until the early 1980's, they have subsequently accumulated tens of millions flight of hours in revenue producing service.

The space shuttle main engine (SSME) and potential advanced earth-to-orbit propulsion systems impose severe conditions on turbopump turbine blades which for some potential failure modes are more severe than in aircraft gas turbines. This paper will discuss research activities which are directed at evaluating the potential for single crystal superalloys for application as turbopump turbine blades in the SSME and advanced rocket engines.

Introduction

In the 1960's, Pratt and Whitney Aircraft pioneered the application of directionally solidified polycrystalline, nickel-base superalloys as turbine airfoils in aircraft propulsion systems. A natural extension of that technology was directionally solidified single crystal castings, which Pratt and Whitney Aircraft introduced into the engines which currently powers some commercial aircraft. Such a single crystal turbine blade for a Pratt and Whitney PW2037 turbofan engine is shown in Fig. 1. Single crystal turbine blades have now accumulated tens of millions of hours of service in both civilian and military aircraft.

The operating conditions for some turbines in advanced rocket engines are in some respects more severe than for aircraft turbine engines. Single crystal airfoils are now being evaluated for some applications in the space shuttle main engine (SSME) and similar propulsion systems. This paper will review selected materials requirements for rocket engine turbine airfoils with particular emphasis on the suitability of single crystal nickel-base superalloys.

Background

The Space Shuttle uses three SSME's during launch. The high pressure fuel and high pressure oxidizer pumps are both driven by combustion turbines which operate under conditions which differ from air breathing aircraft turbines. The operating conditions for advanced rocket engine high pressure turbopump turbines and aircraft turbines

are compared in Table 1. Of particular significance is the fact that rocket turbines may operate in a hydrogen or hydrogen combustion environment at high pressure. This results in very high heat transfer coefficients and resultant severe temperature transients both in the gas stream and metal parts. Figure 2 is a schematic diagram comparing the materials operating realm for SSME and aircraft turbine airfoil materials. Note that the more severe thermal transients in the rocket engine turbines cause a greater strain range than is experienced in aircraft turbines. While the goal life of 7.5 hr (55 launches) appears to be modest for the SSME, the severe low and high cycle fatigue conditions imposed on the turbine blades in a hydrogen environment have so far prevented achievement of the design life goal.

A study was performed by Rocketdyne to assess the relative merits of several classes of materials to lengthen the service life of the turbine blades for an advanced rocket engines like the SSME.¹ The materials considered are shown in Table 2. The study concluded that advanced single crystal superalloys warrant development for turbines operating at 870 °C. A useful advanced single crystal alloy would be one which would be resistant to property degradation in high pressure hydrogen and have fatigue properties superior to those single crystal alloys currently developed for aircraft propulsion.

Single Crystal Superalloys

Mechanical Behavior

Single crystal superalloys offer improved stress rupture life, low and high cycle fatigue life compared to directionally solidified (DS) polycrystalline superalloys. Figure 3 compares those three mechanical properties for NASAIR 100 single crystals and DS MAR-M 247,² the DS alloy from which NASAIR 100 was derived by eliminating carbon, cobalt and boron. Thermal shock testing of single crystal airfoil shapes in a rig which simulates SSME transients demonstrated greater than 70 percent life improvement over MAR-M 246+HF airfoils.³ While the single crystal superalloys offer improvement over DS alloys which are currently bill of materials in the SSME, still further improvements appear to be achievable by the use of advanced processes.¹ These will be discussed later.

Mechanical properties of single crystal superalloys are highly anisotropic. The data comparison in Fig. 3 is for crystals all oriented with an edge of the cubic crystal parallel to the

applied load. Young's modulus at room temperature varies from about 124 GPa for the cube edge direction, $\langle 100 \rangle$ to about 290 GPa for the cube body diagonal direction, $\langle 111 \rangle$. Similarly yield strength, ultimate strength and other mechanical properties are dependent on the crystallographic orientation of the sample or blade and must be considered in the design. The effect of orientation on the LCF life of a single crystal alloy is shown in Fig. 4. It can be seen that when the total strain range is constant, the greatest life is for crystals having a $\langle 100 \rangle$ orientation and the shortest life is for crystals having a $\langle 111 \rangle$ orientation. If, however, the strain is normalized by multiplying by the modulus, all three orientations studied fall on the same line.⁴

Advanced Processes

One failure mode causing severe life limitation in the SSME is fatigue. In conventional carbon bearing superalloys, failure initiation is often associated with carbides. Because most single crystal superalloys contain no intentionally added carbon, the crack initiation site is typically at a pore.

One processing method that has been shown to produce low porosity castings is high gradient directional solidification.⁵ Single crystals grown at 250 °C/cm were found to have about 0.1 percent porosity compared to 0.5 percent for those grown at 50 °C/cm. The latter gradient is typical of the highest gradients commercially available. The crystals grown at 250 °C/cm demonstrated about an order of magnitude improvement in high cycle fatigue life at 870 °C compared to crystals grown at 50 °C/cm as shown in Fig. 5. Currently, there is no commercial production capability having the higher thermal gradient.

An alternative method of reducing porosity is the use of hot isostatic pressing (HIP). It has been used to reduce the amount and size of porosity in superalloy castings for over a decade. Figure 6 shows that the application of HIP to an experimental single crystal superalloy can increase its LCF life threefold.⁶

The application of HIP to improve fatigue properties appears to offer the best near term opportunity for single crystal superalloys. However the process needs to be adapted for the particular alloy and component. Earlier it was mentioned that most single crystal superalloys have no intentionally added carbon. If carbon should inadvertently contaminate the component during HIPing, the incipient melting point of the alloy would be reduced and it may no longer be capable of being properly heat treated. Carbides might also precipitate in the alloy and become crack initiation sites in service. Figure 7 demonstrates that carbon impurities in the HIP atmosphere can react with the alloy and cause both incipient melting and carbide precipitation. In this experimental HIP run, a carbon-free single crystal alloy was HIPed in an autoclave which had a carbon furnace. We believe that the carbon reacted with residual oxygen in the vessel to cause a carburizing atmosphere. The added carbon reduced the incipient melting point to below the working temperature and some melting of the sample occurred. Carbides precipitated on cooling from the HIP temperature. One must carefully control

the atmosphere during the HIP process to avoid such microstructures.

Carbon and boron are usually intentionally added to cast polycrystalline superalloys to strengthen their grain boundaries. Since the single crystal alloys do not have those elements to allow higher temperature solution heat treatment, care must be taken to avoid using parts which inadvertently contain additional grains. Figure 8 is an example of a turbine blade which was thought to have been a single crystal when it was run for about 2 hr in a rotating rig test at elevated temperature.² The blade was in fact designed to operate several thousand hours at a temperature greater than that to which this was exposed, but as can be seen in the figure the blade cracked. It was later concluded that the blade had received abusive handling prior to the solution heat treatment and recrystallized during the solution heat treatment. It should be noted, however, that recrystallization may occur during the casting process or during the HIP process. Thus, all processes must be carefully controlled and inspection methods must be in place to assure that only high quality single crystal blades enter service.

Rocketdyne is studying single crystal superalloys cast by conventional thermal gradient and commercially available high gradient casting processes for application as SSME turbine blades in contract NAS3-24646. The test materials made by both casting processes will be subjected to HIP processing and it is anticipated that a suitable process will be identified for manufacturing single crystal turbine blades with improved fatigue resistance. As a part of the overall SSME program, Rocketdyne is also evaluating the use of conventionally processed and HIP'ed single crystals for application in the high pressure pumps.

Other Considerations:

The SSME turbine blades airfoils operate in a hydrogen - steam mixture. Cooler regions such as the dovetail are exposed to essentially pure hydrogen in the fuel pump. The effects of hydrogen on the mechanical properties must therefore be considered. It is generally accepted that for nickel-base superalloys, the greatest degradation in properties is most likely to occur near room temperature rather than at extreme cryogenic or elevated temperatures.

To screen candidate alloys room temperature tension tests of both smooth and notch bars were performed in 34 MPa hydrogen and helium in the $\langle 100 \rangle$ direction. The tensile strength of several single crystal superalloys in helium is shown in Fig. 9. Note that all alloys are notch strengthened in He. Figure 10 shows the tensile strength of the same alloys tested in hydrogen. Note that most alloys have significantly reduced notch strength compared to smooth bar strength. The degradation of the notch strength in hydrogen is summarized in Fig. 11 which shows the ratio of the notch strength in hydrogen to that in helium. The data appears to fall into three groups. The best alloys, AF56 and N-5, have a ratio of 0.84 and are significantly superior to all others. A second intermediate group of alloys, PWA 1480, RR2000 and N4, have ratios slightly less than 0.5. (It

should be noted that in a subsequent test series PWA 1480 had a notch ratio of 0.59). The remaining alloys have a ratio below 0.4. The single crystal form of the current bill of materials for the SSME, MAR M-246, has a ratio of 0.18 and does not significantly differ from the DS form. One alloy, CMSX-2 was given two different heat treatments. It can be seen that the effect of hydrogen was virtually unchanged. While there has been a great difference in the behaviour of the alloys studied, to date we have been unable to rationalize the differences among alloys.

The amount of plastic deformation sustained by the alloys prior to fracture is lower for specimens tested in hydrogen. The scanning electron micrographs in Fig. 12 compare secondary cracks on the surface of N-5 samples tested in He and H₂. It can be seen that the little plasticity is apparent in the H₂ tested material compared to the one tested in He.

The detrimental effect of porosity on the fatigue life of single crystal superalloys was cited earlier. Recent research has also shown that hydrogen embrittlement is enhanced by the presence of internal voids which trap the hydrogen. Thus, when the material is exposed to conditions which might be expected to allow the hydrogen to escape from the part, the hydrogen may be retained in the pore and still cause embrittlement.

The anisotropy of the mechanical properties of single crystal superalloys was briefly discussed earlier. A high degree of anisotropy is also observed in the effect of hydrogen on a single crystal superalloys. Figure 13 summarizes the degradation of notch tensile strength of PWA 1480 in room temperature hydrogen. The greatest degradation occurs for the <100> direction, while the least is for the <111> direction. (The difference between the 0.59 notch ratio shown here and the 0.49 shown previously is believed to reflect differences in the test lots and may not be significant.) The reason for the degradation in anisotropy is not understood at this time. The implications of this anisotropy on the design of blades are being evaluated.

Concluding Remarks

Single crystal turbine blades are in commercial and military service in gas turbine powered aircraft. An obvious extension of those applications is the use of single crystal materials for

airfoils in the turbines in rocket engines. Current technology single crystal alloys offers the potential for improved life in SSME turbines and advanced processing offers potential for even greater improvements. Programs are currently in progress to evaluate the potential for single crystal alloys for rocket engines for earth-to-orbit propulsion systems and it is expected that these newly developed alloys will soon be flight qualified for such systems.

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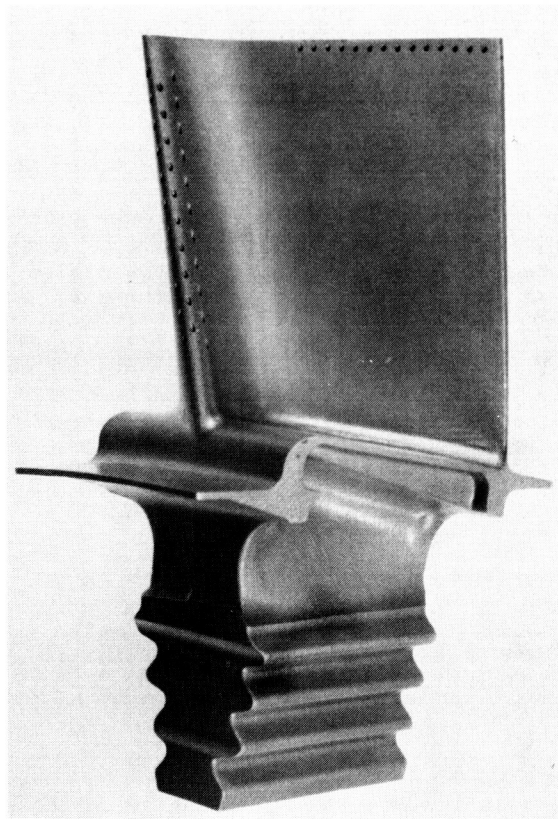
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TABLE I. - COMPARISON OF ROCKET ENGINE AND AIRCRAFT ENGINE
TURBINE OPERATIONS

Item	Rocket engines	Aircraft engines
Fuel	Hydrogen or methane	Petroleum distillate
Oxidizer	Oxygen	Air
Pressure, psi	5 500 psi	400
Speed, rpm	36 000 to 110 000	15 000
Tip speed, ft/sec	1 850	1 850
Horsepower/blade	630	200 to 500
Inlet temperature, °F	1 600 to 2 200	2 600
Heat transfer coefficient	54 000	500
Btu/ft ² hr-°F		
Thermal transients	32 000	100
°F/sec		
Starts	55 to 700	2 400
Life, hrs	7.5 to 100	8 000

TABLE II. - POTENTIAL ADVANCED
BLADE MATERIALS

Directionally solidified MAR-M 246+Hf
Single crystal superalloys
Directionally solidified eutectic alloys
Fiber reinforced superalloys
Rapid solidification superalloys
Monolithic ceramics



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FIGURE 1. - SINGLE CRYSTAL TURBINE BLADE
USED IN PdWA 2037 ENGINE.

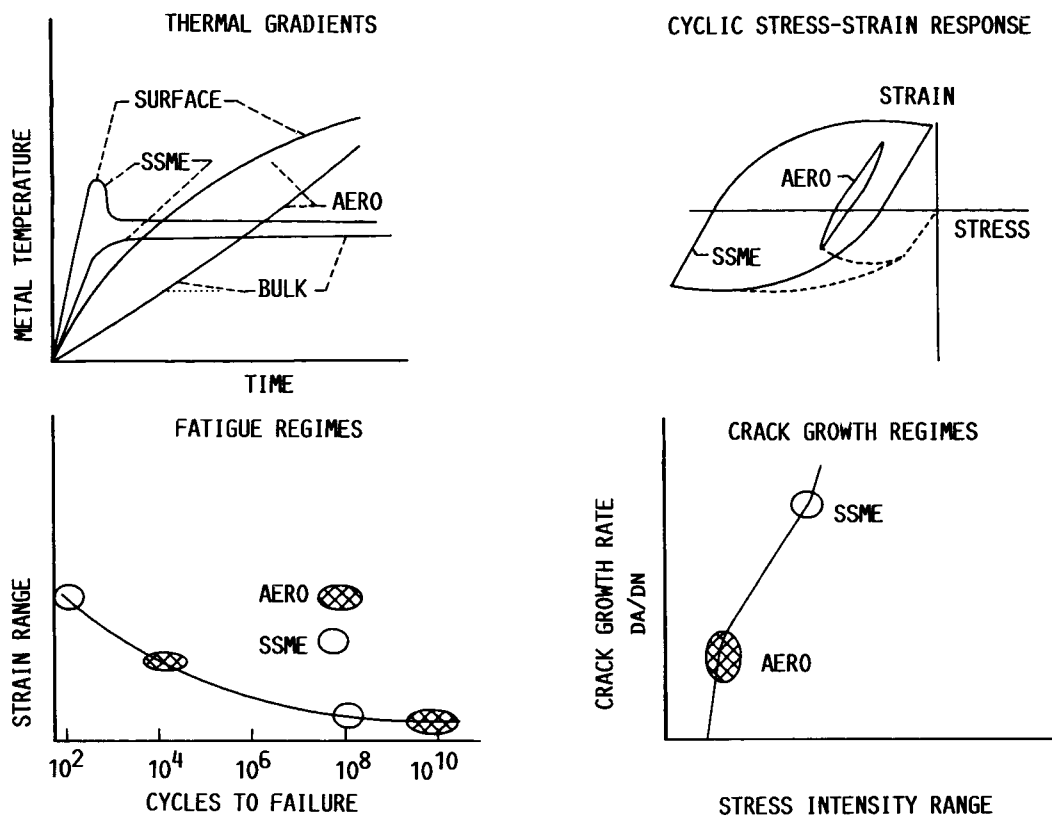


FIGURE 2. - COMPARISON OF SSME AND AERO TURBINE BLADE MATERIALS OPERATING REGIMES.

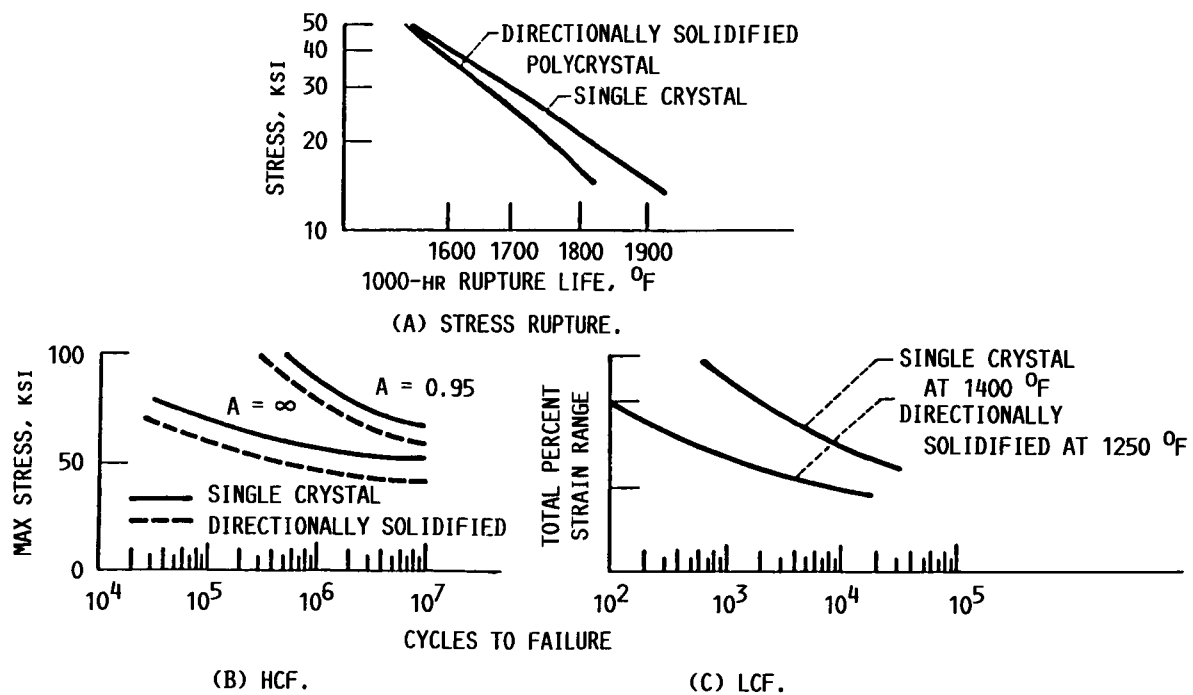


FIGURE 3. - SINGLE CRYSTAL ALLOYS HAVE MECHANICAL PROPERTIES SUPERIOR TO DIRECTIONALLY SOLIDIFIED ALLOYS.

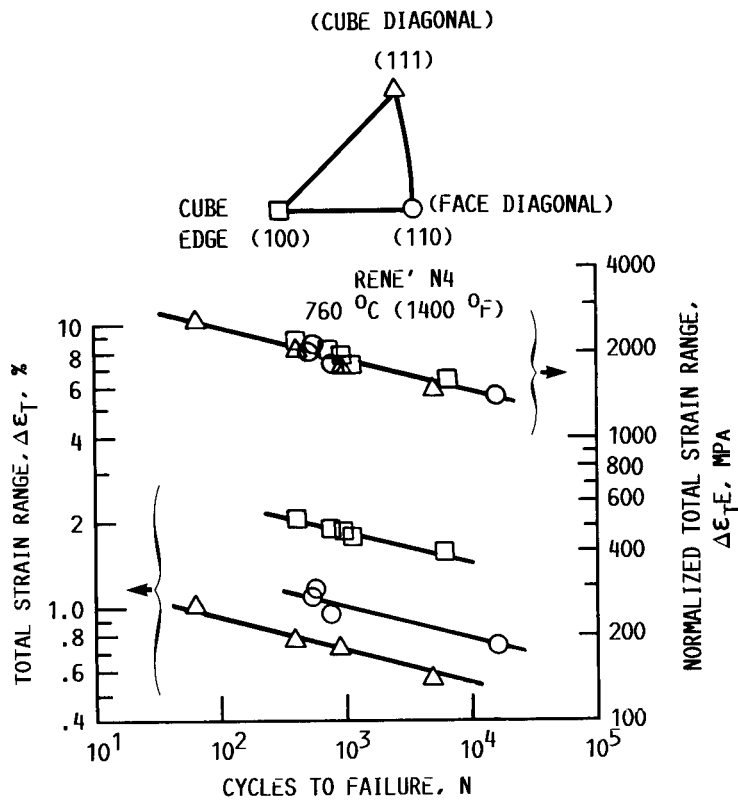


FIGURE 4. - LCF ANISOTROPY OF A SINGLE CRYSTAL SUPERALLOY.

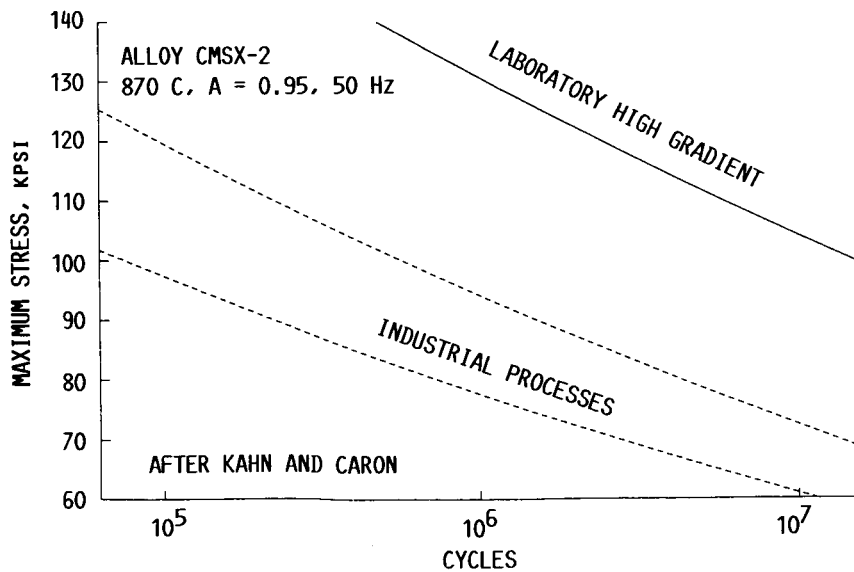


FIGURE 5. - HIGH GRADIENT SOLIDIFICATION IMPROVES HIGH CYCLE FATIGUE LIFE OF SINGLE CRYSTALS.

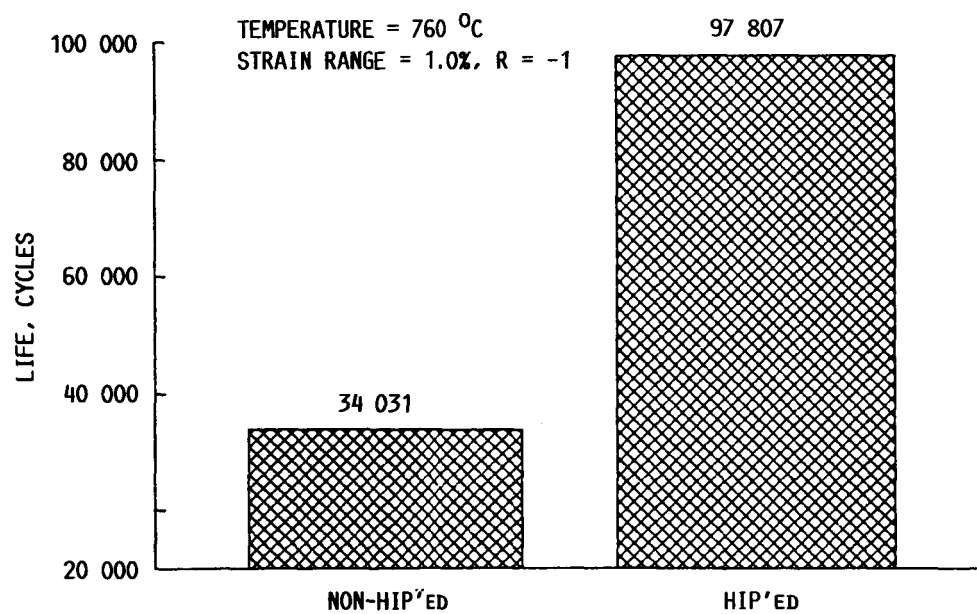
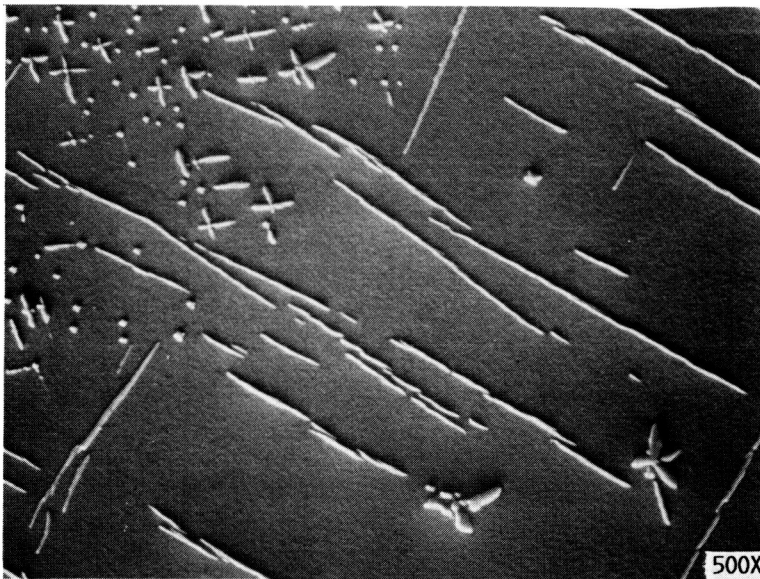
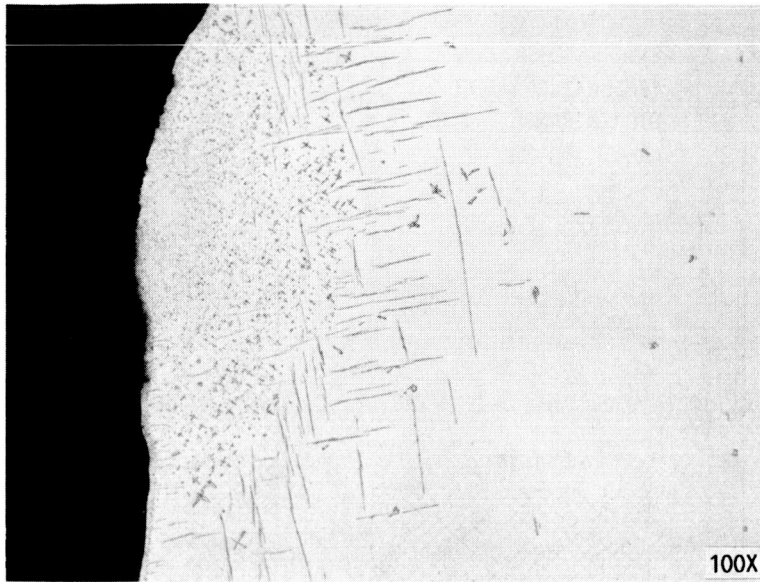


FIGURE 6. - HIP IMPROVES LCF LIFE OF SINGLE CRYSTALS.

DATA FROM JABLONSKI AND SARGENT

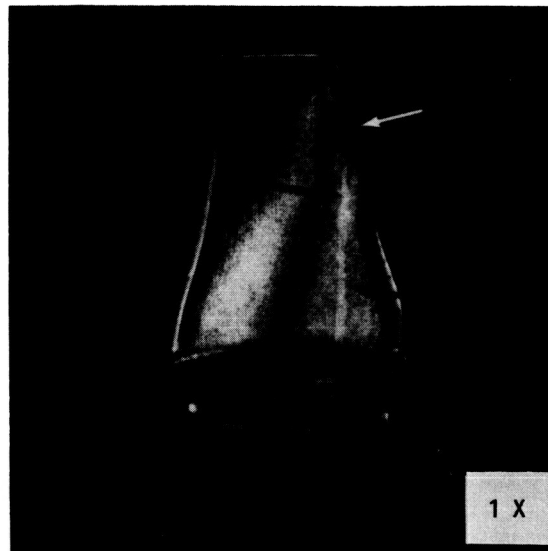
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ALLOY CMSX 2
HIP 2 HR, 2380 °F

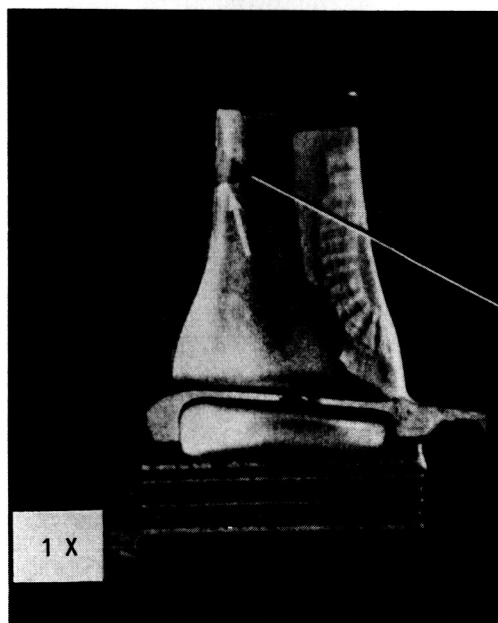
FIGURE 7. - HIP ATMOSPHERE CAN CAUSE CARBURIZATION AND MELTING.

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BLADE A25

CRACK OPENED FOR STUDY



BLADE A41

APPROX. 1 HR IN ROTOR RIG

FIGURE 8. - SINGLE CRYSTAL ALLOYS WILL NOT TOLERATE RECRYSTALLIZATION.

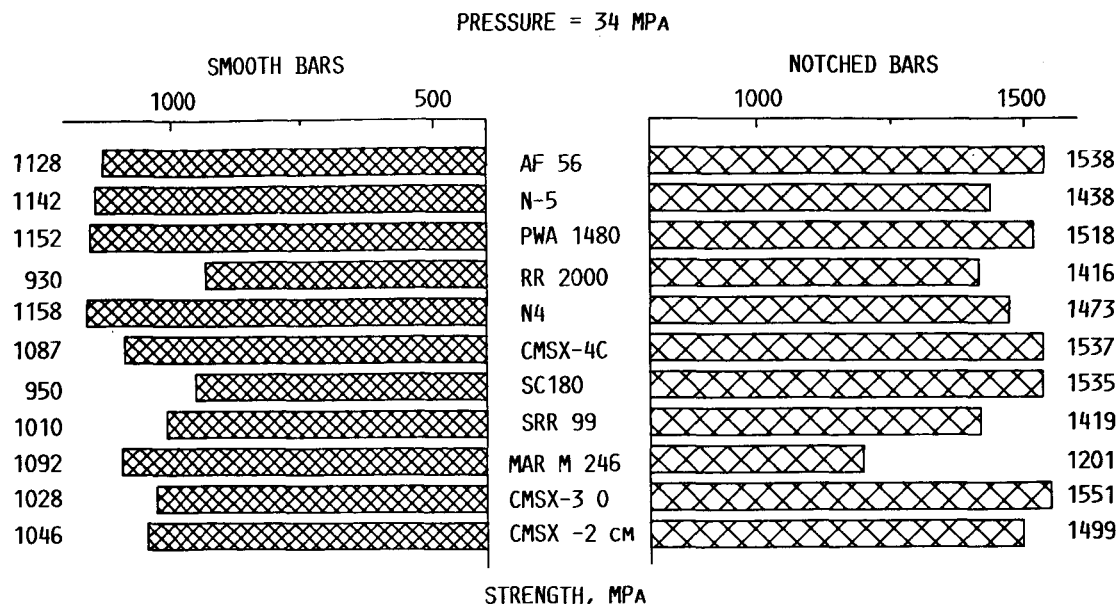


FIGURE 9. - TENSILE STRENGTH OF SINGLE CRYSTAL SUPERALLOYS IN HIGH PRESSURE HELIUM.

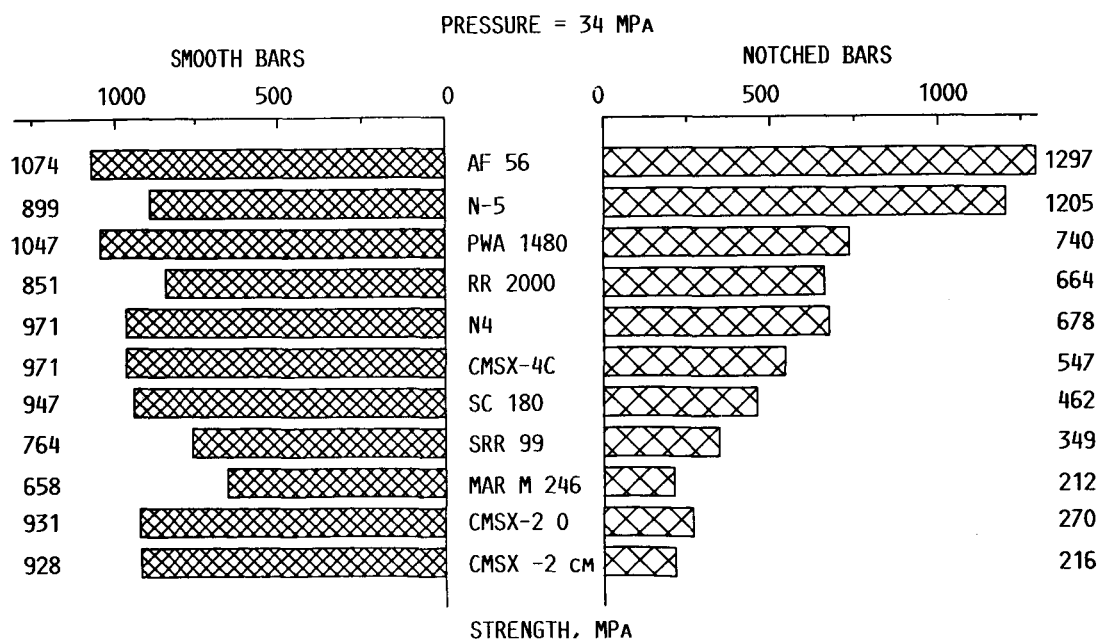


FIGURE 10. - TENSILE STRENGTH OF SINGLE CRYSTAL SUPERALLOYS IN HIGH PRESSURE HYDROGEN.

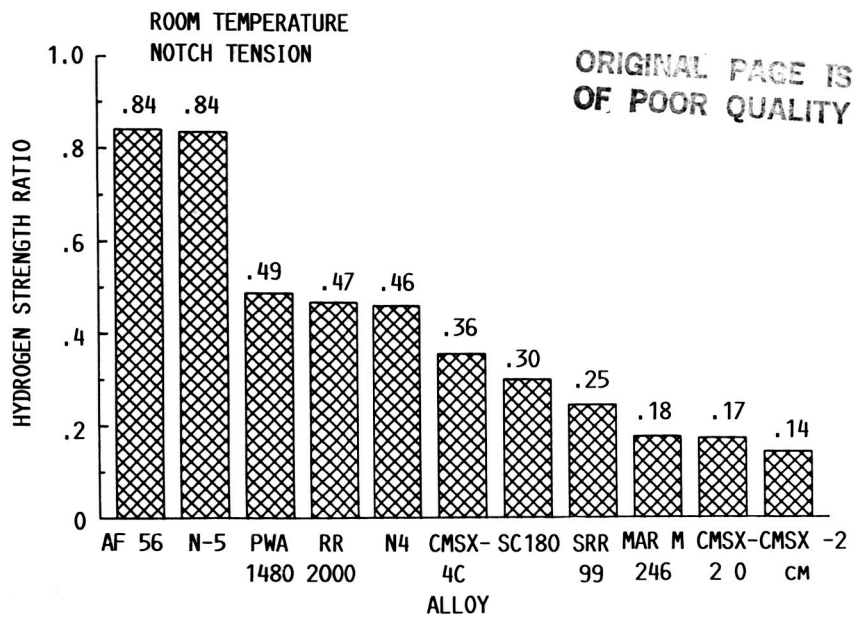
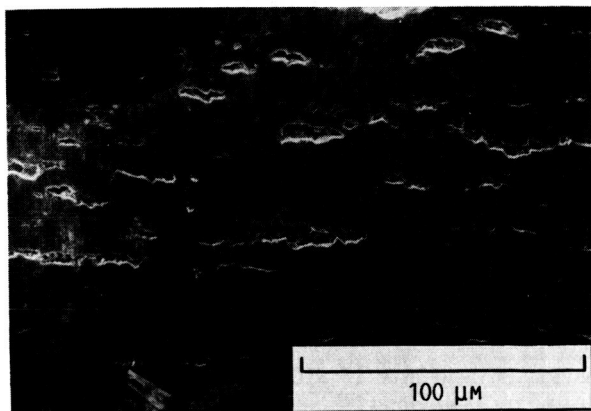
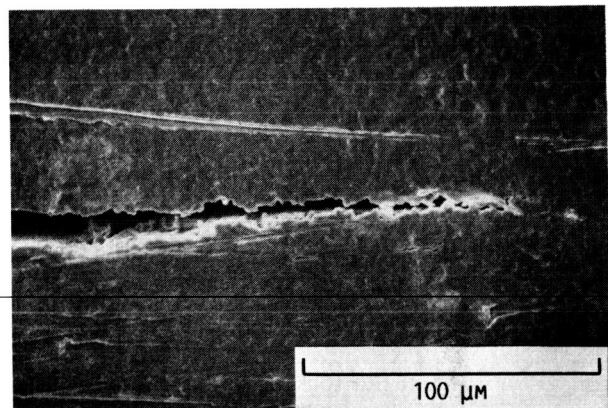


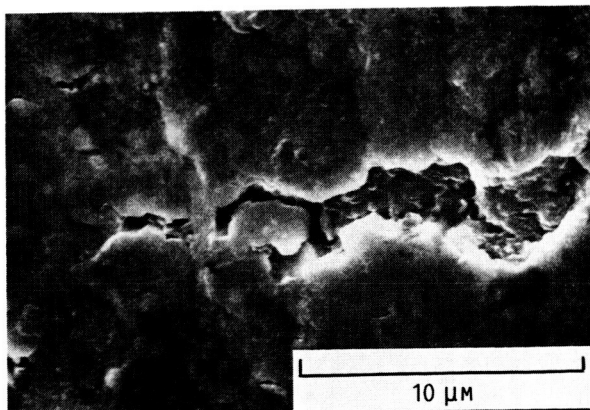
FIGURE 11. - RANKING OF SINGLE CRYSTAL SUPERALLOYS IN HIGH PRESSURE HYDROGEN.



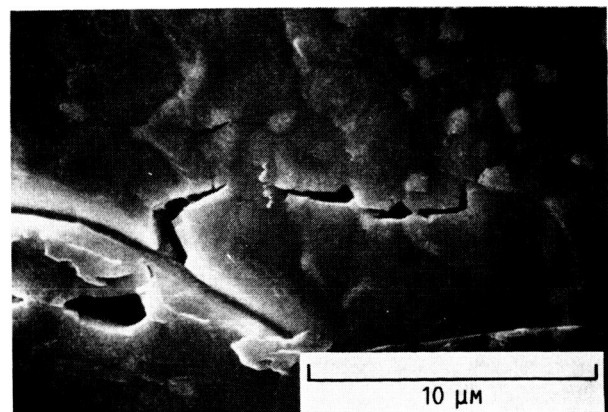
HELIUM



HYDROGEN



HELIUM



HYDROGEN

FIGURE 12. - TENSILE TESTS IN HYDROGEN HAVE LITTLE PLACIDITY.

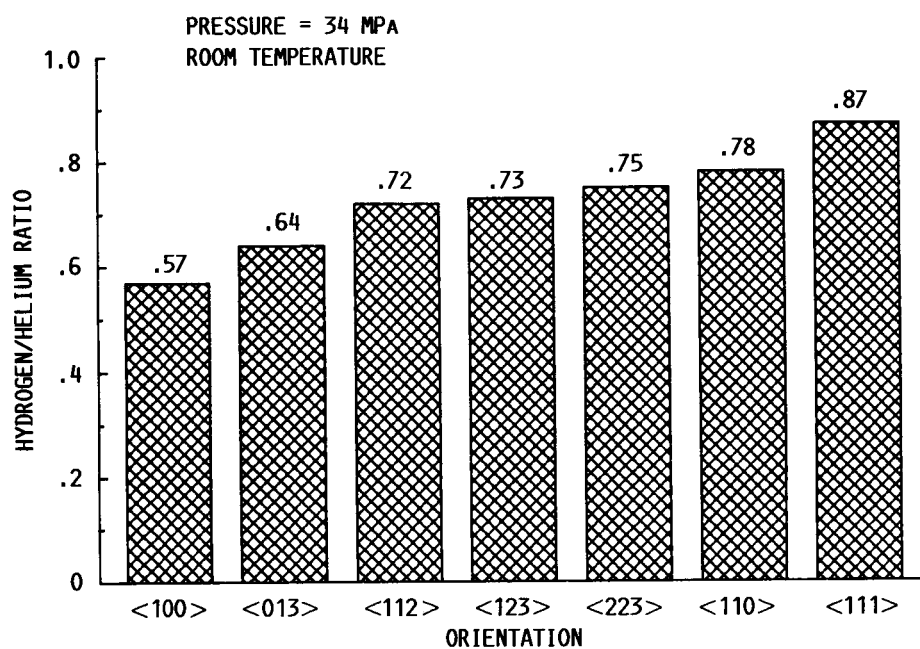


FIGURE 13. - ANISOTROPY OF DEGRADATION OF STRENGTH IN HIGH PRESSURE HYDROGEN OF A SINGLE CRYSTAL SUPERALLOY, PWA 1480.

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