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EFFECTS OF THERMALLY INDUCED POROSITY ON AN AS-HIP POWDER METALLURGY SUPERALLOY

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INTRODUCTION

Recent advances in the processing of superalloys from atomized-prealloyed powder have permitted their commercial use for highly stressed components such as disks for aircraft gas turbine engines. In the development of these components, parts were first made by the hot working of compacted powdered metal billets, and more recently by hot-isostatically compacting the prealloyed powders directly to near final shape without subsequent hot working. The manufacturing processes to produce hot-isostatically-pressed (HIP) parts are described elsewhere.[1,2]

Among the concerns for manufacturing a reproducible high quality product is that of maintaining low levels of thermally induced porosity (TIP). TIP is caused by entrapped insoluble gases, principally argon (Ar). which expand during post HIP thermal treatments leaving discontinuous porosity in the product. Argon may be introduced from at least three sources. First, if the powder is produced by Ar atomization, some powder particles may actually be bubbles with Ar inside. Second, if the powder is not sufficiently outgassed before pressing, it may contain adsorbed Ar. And finally, if the container holding the powder leaks, Ar, which is the pressing medium used in high temperature autoclaves, will be pumped into the container. The first two types of TIP would be expected to produce a relatively uniform distribution of pores throughout the body.

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The third type might be expected to result in the formation of a porosity gradient, the highest porosity being at the leak site. It is this third type of TIP which was studied in the work reported here. Manufacturer's specifications for TIP are based on density change, typically a few tenths of a percent, or metallographic evaluation after a high temperature exposure.[1,2] Metallographically acceptable pressings typically have less than 0.1% spherical porosity and essentially no porosity at grain boundary triple points. It is generally accepted that the presence of TIP can be detrimental to a part; however, little information has been made available on the quantitative effects of TIP on mechanical properties. This paper reports on an investigation which was initiated to determine the effects of excessive TIP which occurred as a result of an actual manufacturing incident. Mechanical properties of a porous HIP superalloy part are compared with similar parts which met industrial acceptance criteria.

Material and Experimental Procedures

The alloy studied in this investigation was HIP low carbon Astroloy. All of the material was taken from full scale pressings for turbine disks of a commercial aircraft gas turbine engine. The target shape for the pressings is shown in Fig. 1. The final machined configuration of the disk is shown by a broken line. The parallel sided shape of the pressing is designed for ease of ultrasonic inspection. The processing of these disks is fully described elsewhere[1] and will only be briefly discussed here.

The chemical specification for low carbon Astroloy is shown in Table 1. All disks were produced from -80 mesh powder. The powder was loaded in mild steel cans, hot outgassed, sealed, and hot isostatically pressed in argon for 3 hours at 1190 or 1215°C and a pressure of 103 MPa. Following container removal, the pressings were heat treated as follows: 1115°C/2 hrs/AC+870°C/8 hrs/AC+980°C/4 hrs/AC+650°C/24 hrs/AC+760°C/8 hrs/AC.

One pressing cracked during heat treatment.[1] Examination also showed that it exceeded the engine manufacturer's specification for TIP. The manufacturers TIP test consisted of heating a sample at 1205°C for 4 hours followed by comparative metallographic examination. This porous pressing was donated by its manufacturer for the present study. All of the "sound" pressings tested met the specification for TIP and were shown to be free of rejectable defects by ultrasonic inspection.

Tensile, stress-rupture, and creep tests were performed in accordance with appropriate ASTM recommended practices. For the stress-rupture test, a combination smooth-notch bar was used, the notched section having a stress concentration factor of 3.9. Strain-controlled fully-reversed low cycle fatigue tests were conducted at 650°C and 0.33 Hz. Creep-fatigue tests were identically conducted except for a 900 second dwell at maximum tensile strain. Loading and unloading rates were constant and equal and the same for both types of tests. These test methods are fully described in Ref. 3.

The tensile, stress-rupture, and creep properties for "sound" HIP Astroloy used here as a reference baseline are those of the seven pressings described in Reference 1, plus those of an additional pressing,[4] which was used for determination of the fatigue and creep-fatigue behavior.[3] The mechanical properties for the "sound" HIP Astroloy are the data reported in those investigations.

RESULTS AND DISCUSSION

The cracked pressing studied in this investigation exhibited excessive TIP as determined by metallographic examination of a sample taken from the fill stem which was located on the rim of the pressing. The appearance of the porous microstructure is compared with an acceptable structure in Fig. 2. The density of a sample of heat treated rim material decreased 6.7% when it was heated at 1205°C for 4 hours.

Material from the pressing itself has less, though still appreciable, porosity because the maximum temperature it experienced was the 1115°C solution treatment compared to 1205°C for the TIP test. Unetched photomicrographs of the rim are shown in Fig. 3 and of the bore in Fig. 4. The porosity appears to outline the prior particle boundaries and suggest that poor bonding between powder particle has occurred during the consolidation treatment. Comparison of the micrographs shows that there is considerably greater porosity at the bore. Quantitative evaluation of photomicrographs of test bars showed the bore of the pressing to contain about 2.6% porosity compared to 1.4% near the rim. This is in agreement with water displacement density measurements made on a sample of bore and of rim material which showed 1.6% lower density at the bore. It is presumed that a defect in the can at the bore allowed Ar to leak in during pressing.

The properties of all sound pressings are very consistent; however, within each pressing there are small but significant differences depending on location. Mechanical properties of alloys such as Astroloy are known to be a function of cooling rate from the γ' solution treatment temperature and, therefore, a function of section thickness. Fig. 1 shows that the section thickness of the pressing studied varies considerably; however, data obtained in Reference 1 shows that the mechanical property may for simplicity be divided by location into just two groups. One group is for locations near the rim of the disk. The second group is for thicker sections at the web and bore of the disk. In this paper, data from the bore and web regions shown in Fig. 1 are grouped and called bore data, and data from the integral ring, seal band, and rim are grouped and called rim data.

The ultimate tensile strengths at room temperature and 538°C of the porous pressing and sound pressings are compared in Fig. 5. The average strength at room temperature in the rim of sound pressings was 1375 MPa. For the porous pressing, the average strength in the rim at room temperature was only 5% lower, being 1305 MPa. The average strength of the sound pressing in the bore was 1360 MPa, only slightly less than in the rim. However, for the porous pressing, the average strength in the bore was only 1127 MPa, 14% less than at the rim, and 17% less than in the bore of the sound pressings. At 538°C, the strength at the rim averaged 1277 MPa for the sound pressings and was only 4% less for the porous disk, 1223 MPa. But, as at room temperature, the strength of the bore was considerably less, 11%, for the porous pressing, 1123 MPa rather than 1262 MPa.

All tests performed on material from the rim of both the sound pressings and the porous one at both room temperature and 538°C met the minimum values of ultimate tensile strength for acceptance of the part. Also, for the sound pressings, all the ultimate strengths measured on bore material were acceptable. However, of the four tests performed on bore material from the porous pressing, only one test, at 538°C, exceeded the specified minimum value. It should be noted that for the porous pressing, the average strength at both rim and bore at both test temperatures fell below the minimum strength values measured for sound pressings.

The 0.2% yield strengths of the sound and porous pressings at room temperature and 538°C are shown in Fig. 6. The data show the same trends as noted for the ultimate strength; the porous pressings having lower yield strength than the sound pressings, particularly at the bore. As was noted for the ultimate strengths, the yield strengths for both the sound and porous pressings at both temperatures in the rim region exceeded the minimum specified values. Also, bore yield strengths were acceptable for the sound pressings, but 3 of the 4 bore test values for the porous pressing were below the minimum specified.

The tensile ductilities of the porous and sound pressings at room temperature and 538°C are compared in Fig. 7. Unlike the yield or ultimate tensile strengths, the ductilities of the porous pressing were considerably lower at both rim and bore than for the sound pressings. The maximum ductility measured for the porous pressing were below the minimum ductility for the sound pressings for all cases except in the rim at 538°C where the maximum value for the porous pressing was about equal to the average of the sound pressings. Of the 12 tensile tests conducted on the porous disk, results of 2 tests at the bore and 3 tests in the rim regions were below the minimum specified for reduction in area, while only 2 tests of the bore were below the minimum specified for elongation. For the sound pressings, the ductility at the bore appears to be slightly greater than at the rim which is consistent with the reduced strength level at the bore caused by slower cooling.[1,2] For the porous pressing, the bore's ductility is clearly lower than the rim's ductility which is attributed to the bore having a greater level of porosity.

Stress rupture tests were performed at 732°F with applied stresses of 552 and 621 MPa and at 760°C with an applied stress of 552 MPa. As indicated earlier, the tests were performed using a combination notch/smooth bar. All fractures occurred in the smooth section. Figure 8 compares the geometric average, maximum and minimum lives for sound and porous pressings. At the bore, the lives of the porous pressing were much lower than the lives of the sound pressings, while at the rim, the degradation of life for the porous pressing was not as severe. At the specification test condition, 732°C with a stress of 552 MPa, the rims of both porous and sound pressings had indistinguishable lives which exceeded the specified minimum of 23 hours.

Fig. 9 compares the stress rupture elongation of sound and porous pressings. It can be seen that the elongation at the bore was always much lower for the porous pressing than for the sound pressings. At the specified test condition of 732°C and 552 MPa, the test results at the rim were essentially the same for both porous and sound material and the specified minimum of 8% was exceeded in the rim. However, in both of the tests performed on samples from the bore of the porous pressing, the elongations were below 8%. For the sound pressings, the bore tended to have elongations equal to or perhaps even greater than the rim.

The specification for material acceptance also requires that at 704°C and a stress of 510 MPa, the time to exceed 0.1% creep be equal or greater than 100 hours. In six tests from the rim of sound pressings, the time for 0.1% creep varied from 162 to 256 hours with an average of 207 hours. In four tests of rim of the porous pressing, two were below the minimum of 100 hours; that time ranged from 65 to 117 hours, and averaged 81 hours. No creep tests were performed at the bore.

The low cycle fatigue behavior at 650° C of material from the rim of a porous and sound pressing are compared in Fig. 10 for .33 Hz testing and in Fig. 11 for creep-fatigue testing with a 900 second dwell at the maximum tensile load. At the lives to which commercial aircraft engine disks are designed (10^4 cycles), the strain range capability of the porous pressing was only slightly reduced compared to the sound pressing. In the lower life-higher strain range, the porous material appears to be inferior to the good material. It should be noted that the low cycle fatigue and creep fatigue tests were performed on material from the rim region of the pressings. This is the lower porosity region of the porous pressing.

CONCLUDING REMARKS

It is apparent that the porous pressing examined had a porosity gradient with the bore region having considerably greater porosity than the rim and that some mechanical properties were degraded by the porosity. For the pressing studied, the integral test ring (the portion used for acceptance testing) is located near the rim and except for slightly low ductility on a few tests and somewhat excessive creep rate, the test ring material met the minimum mechanical property requirements for acceptance. At the bore, however, one tensile test was slightly below the minimum specified ultimate strength for 538°C and another was 17% below the minimum ultimate strength for room temperature. The tests at the bore having low strengths also had low ductility. It therefore appears plausible that in a part such as the one studied that an integral test ring may have acceptable strength levels while other regions remote to the test ring may not. Thus, it would appear prudent to examine several sections of such a part at several radial and circumferential locations with TIP tests for porosity characteristics prior to accepting it for use.

SUMMARY

An investigation was performed to determine the effect of thermally induced porosity on the mechanical properties of an as-hot-isostatically pressed and heat treated pressing made from low carbon Astroloy. It is believed that the mild steel can crack during the HIP cycle allowing the Ar pressing medium to be pumped into partially consolidated metal powder thereby causing excessive TIP. Tensile, stress-rupture, creep, and low cycle fatigue tests results are summarized below:

1. A porosity gradient existed from the rim to the bore of the pressing with the bore having about 1½% greater porosity.

2. The porous pressing which had excessive TIP would have been rejected on the basis of the acceptance criteria established for the mechanical properties of the integral test ring. Mechanical properties of the test ring below acceptance levels were tensile reduction in area at room temperature and 538°C and time for 0.1% creep at 704°C.

3. The strength, ductility, and rupture life of the rim of the porous pressing were slightly inferior to the rim of the sound pressings.

4. The strength, ductility, and rupture life of the bore of the porous pressing were significantly degraded when compared to sound pressings, and were generally below acceptable specification levels.

5. At strain ranges typical of commercial aircraft engine designs, the rim of the porous pressing had slightly inferior low cycle fatigue life than the sound pressings, however, the low cycle fatigue tests were performed at the lower porosity region of the porous pressing.

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2. P. S. Mathur and J. L. Bartos, no company rept. # Final Report - July 1973 - July 1976, General Electric Company, Lynn, MA, May 1977. (USAAMRDL-TR-76-30, AD-A043688).
3. B. A. Cowles, D. L. Sims, and J. R. Warren, PWA-FR-10299, Pratt & Whitney Aircraft Group, West Palm Beach, FL, October 1978. (NASA CR-159409)
4. B. A. Cowles, private comm.

TABLE I. - CHEMICAL SPECIFICATION FOR LOW CARBON ASTROLOY

	min	max
Carbon	0.02	0.04
Manganese	------	.15
Silicon	------	.20
Phosphorous	------	.015
Sulfur	------	.015
Chromium	14.00	16.00
Cobalt	16.00	18.00
Molybdenum	4.50	5.50
Titanium	3.35	3.65
Aluminum	3.85	4.15
Boron	.015	.025
Zirconium	------	.06
Tungsten	------	.05
Iron	------	.50
Copper	------	.10
Lead	------	.0010 (10 ppm)
Bismuth	------	.00005 (0.5 ppm)
Oxygen	------	.010 (100 ppm)
Nitrogen	------	.0050 (50 ppm)
Nickel	remainder	

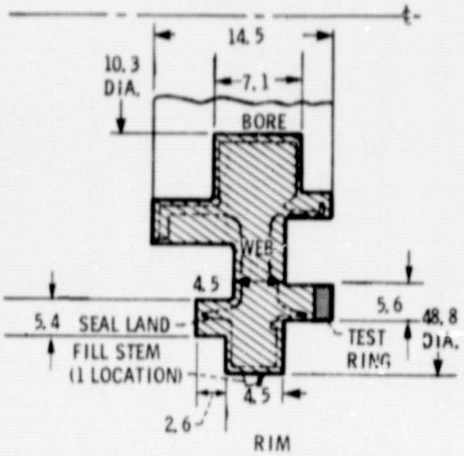

Figure 1. - Target shape for turbine disk pressing. (Dimensions in cm.)

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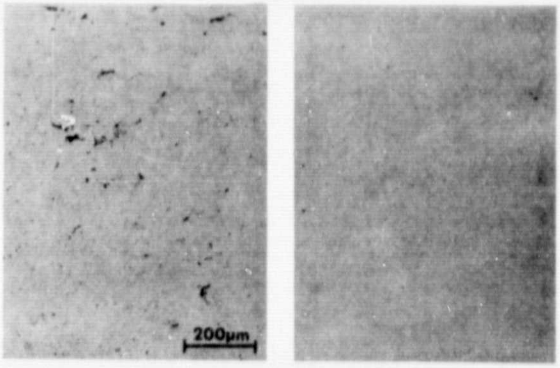

POROUS SOUND

THERMALLY INDUCED POROSITY TESTS OF DISKS.

Figure 2. - Micrographs of specimens taken from the fill stem, near rim of disk; unetched.

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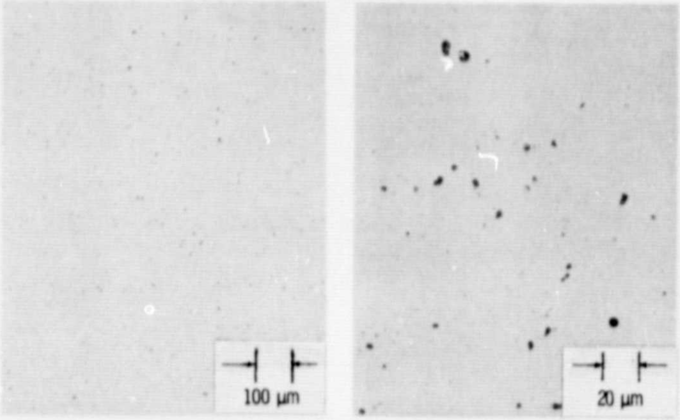

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Figure 3. - Microstucture of porous pressing rim.

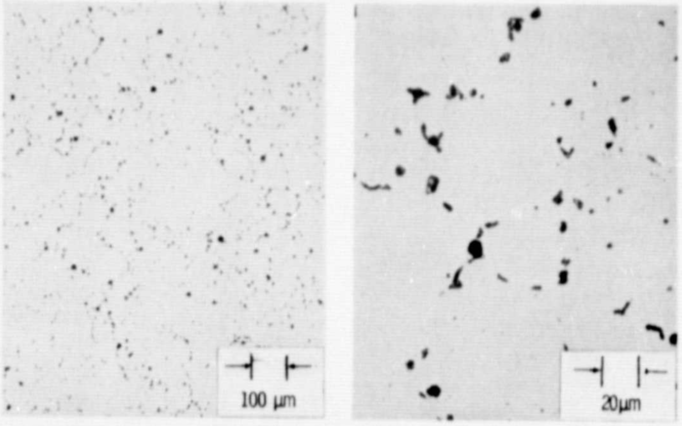

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Figure 4. - Microstructure of porous pressing bore.

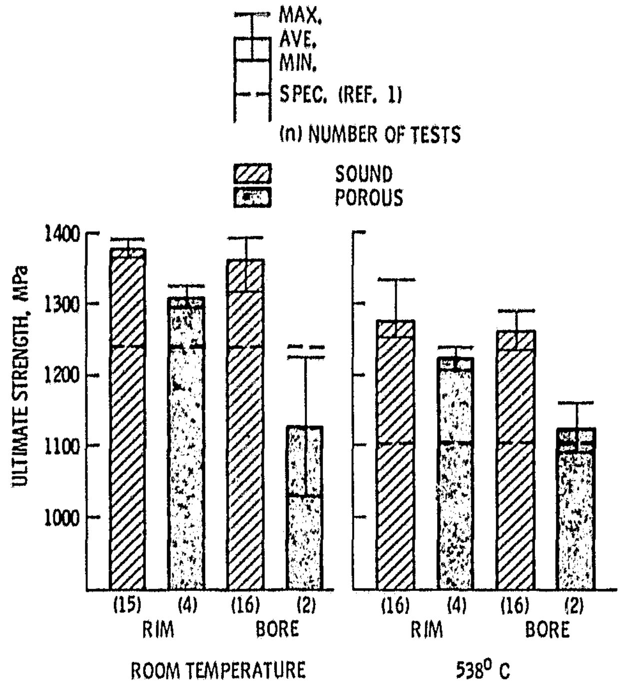

Figure 5. - Effect of TIP on ultimate strength.

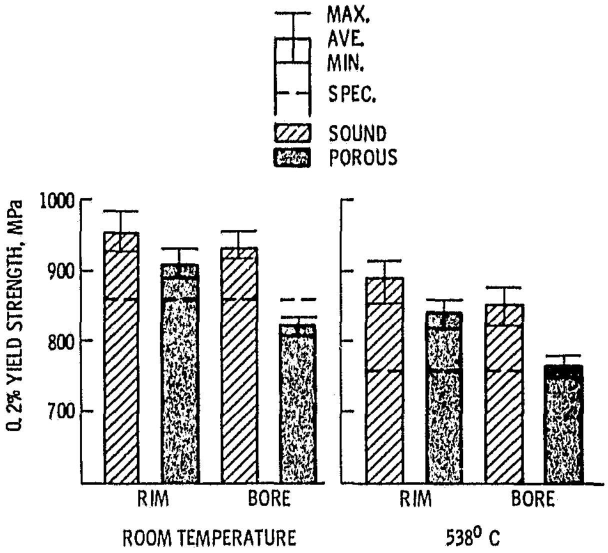

Figure 6. - Effect of TIP on yield strength.

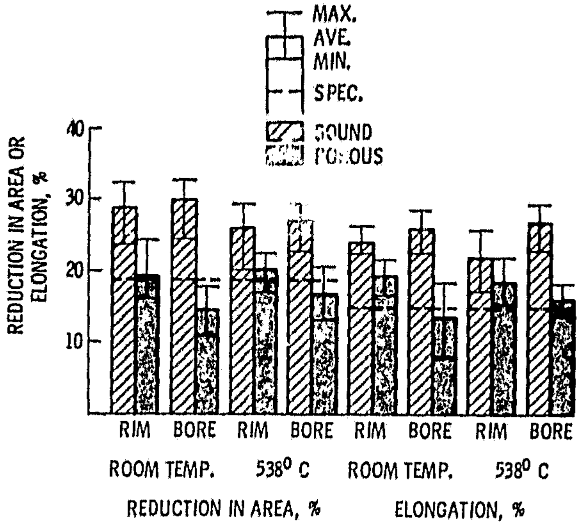

Figure 7. - Effect of TIP on tensile ductility.

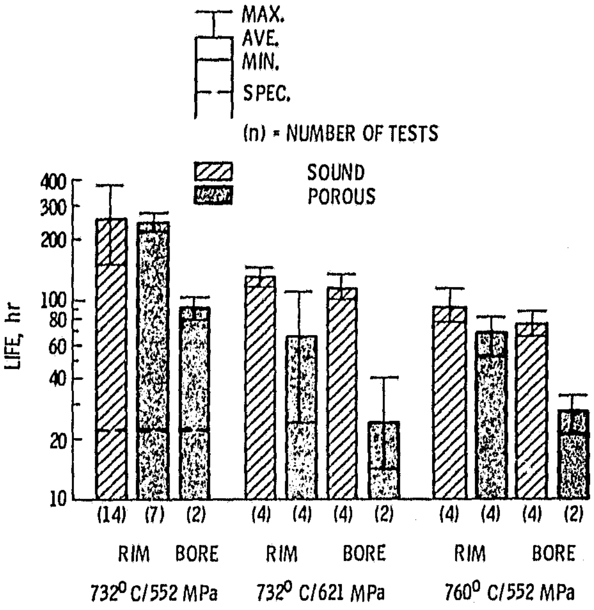

Figure 8. - Effect of TIP on stress rupture life.

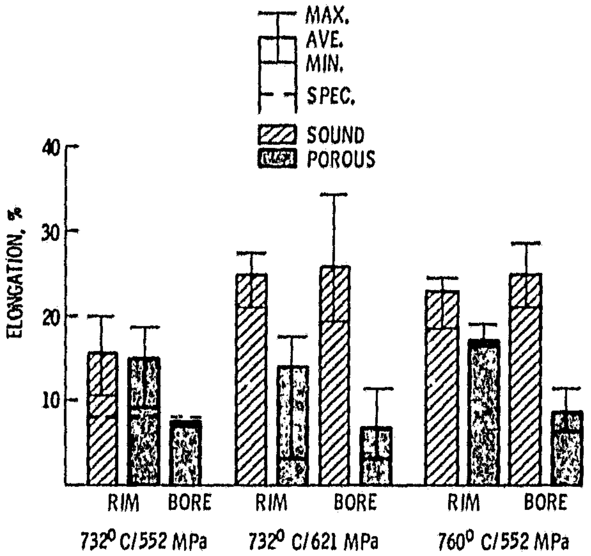

Figure 9. - Effect of TIP on stress rupture elongation.

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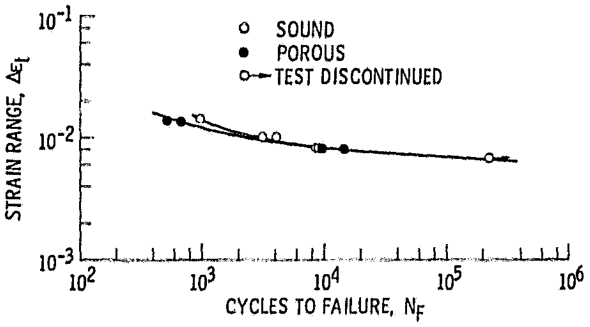

Figure 10. - Relationship between total strain range and fatigue life for porous and sound HIP Astroloy at rim, 650° C, 0.33 Hz, R = -1.

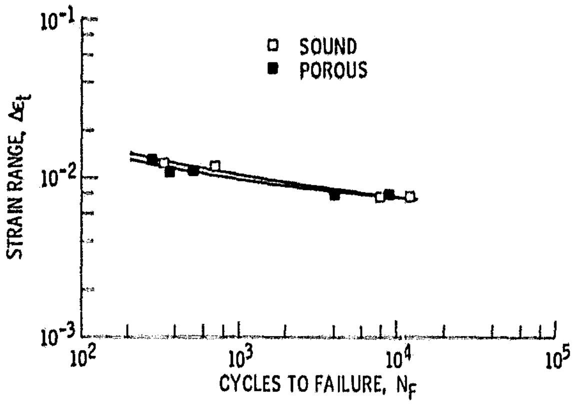

Figure 11. - Relationship between total strain range and fatigue life for porous and sound HIP Astroloy at rim, 650° C, 900 s tensile dwell, R = -1.