EVALUATION OF MECHANICAL PROPERTIES

OF A LOW COBALT WROUGHT SUPERALLOY

Robert L. Dreshfield

National Aeronautics and Space Administration
Lewis Research Center
21000 Brookpark Road
Cleveland, Ohio 44135
USA

Abstract

In the late 1970's and early 1980's the metal cobalt was subjected to significant supply and market pressures. Those pressures caused renewed attention to the use of cobalt in aircraft engines. A NASA sponsored program called COSAM (Conservation of Strategic Aerospace Materials) was created in response to the supply problems with cobalt and other aerospace metals. Among the work performed in the COSAM program and simultaneously by others, were several studies on laboratory size heats of wrought nickel-base superalloys. These studies suggested that the cobalt levels of the alloys might be reduced by about half with little negative impact on mechanical properties.

The Lewis Research Center procured a 1365 kg (3000 lb) heat of a modified Waspaloy having a reduced cobalt level. This paper reports the results of a program performed at four gas turbine manufacturers which evaluated the mechanical properties of forgings fabricated from that heat.

The alloy chemistry selected reduced the nominal Co level from 13.5 to 7.75 wt %. To compensate for the anticipated strength reduction caused by a slight reduction in the amount of γ', the nominal aluminum was increased from 1.3 to 1.5 percent and the titanium was increased from 3.0 to 3.2 percent. The increase in Al and Ti were intended to increase the amount of γ' in the alloy.

Tensile, creep rupture, low cycle fatigue and cyclic crack growth tests were performed. In addition the effect of hydrogen on the alloy was determined.

It is concluded that, in the event of a cobalt shortage, a low cobalt modification of Waspaloy could be substituted for Waspaloy with little development in those applications which are not creep rupture limited. With some additional development to better control the grain size, it is probable that most of the current Waspaloy requirements might be met with a lower cobalt alloy.

Superalloys 1992
Edited by S.D. Antolovich, R.W. Stusrud, R.A. MacKay,
D.L. Anton, T. Khan, R.D. Kissinger, D.L. Klarstrom
The Minerals, Metals & Materials Society, 1992

Introduction

In the late 1970's and early 1980's the metal cobalt was subjected to significant supply and market pressures which caused renewed attention to its use in aircraft engines. Work was initiated to evaluate cobalt use for aircraft engines as part of the NASA sponsored "COSAM" (Conservation Of Strategic Aerospace Materials) program.[1] Four metallic elements, Co, Cr, Nb and Ta were selected by NASA for emphasis in the COSAM program in an attempt to find technology based approaches to reduce the dependence of the United States aircraft engine industry on potentially unreliable foreign sources for those metals.

During the three year life of the COSAM program considerable progress was made in understanding the effects of Co on the properties of several Ni-base superalloys using laboratory size heats. It appeared that several commercial alloys might have their cobalt levels reduced without significantly deteriorating their mechanical properties. The ASME Gas Turbine Panel recommended that NASA and the aircraft engine industry cooperatively evaluate a production size heat of Waspaloy having a reduced level of cobalt. The results of that evaluation are described in this paper.

Alloy selection and processing

Based on previous work performed at Special Metals,[2] Columbia University[3] and Purdue University[4] and private communication with Professor John Tien a target chemistry for low cobalt Waspaloy based on AMS 5704C[5] (Waspaloy) was selected. The standard AMS 5704C and selected chemistries are shown in table I. The nominal level of Co was reduced from 13.5 to 7.75 wt % and Ti and Al were increased from 3.0 and 1.3 to 3.2 and 1.5 percent respectively. The increase in Ti and Al were intended to compensate for the slight loss in the amount of γ' expected from the increase in Ni resulting from the changes.

Table I Composition of Alloys, wt %

	AMS 5704C		Low Co Waspaloy	
Element	Minimum	Maximum	Minimum	Maximum
Carbon	0.02	0.10	0.02	0.10
Chromium	18.00	21.00	18.00	21.00
Cobalt	12.00	15.00	6.5	9.0
Molybdenum	3.50	5.00	3.5	5.00
Titanium	2.75	3.25	3.0	3.4
Aluminum	1.20	1.60	1.3	1.7
Zirconium	0.02	0.08	0.02	0.08
Boron	0.003	0.10	0.003	0.10
Nickel	Balance			

A 1365 kg (3000 lb) vacuum induction melted-vacuum arc remelted heat of the modified alloy was procured from Special Metals Corporation by the Wyman Gordon Company. The 51 cm (20 in.) diameter VIM/VAR ingot was homogenized for 48 hr at 1205 °C (2200 °F). The ingot was drawn to 28 cm (11 in.) diameter at 1190 °C (2175 °F) and finished at 23 cm (8-7/8 in.) diameter at 1160 °C (2125 °F). The billet was then ground to 20 cm (8 in.) diameter and contact sonic inspected to a number 3 flat bottom hole. The billet was cut to

22 cm (8.5) in. long (56 kg (123 lb)) forging multiples which were upset at 1110 °C (2025 °F) in a 9100 kg (20 000 lb) hammer forge and finished at 1095C (2000 °F) in a 16 000 kg (35 000 lb) hammer to the disk shape shown in figure 1. Eight forgings were made.

The γ' solvus temperature was determined by differential thermal analysis to be 1058 °C (1937 °F). The forgings were solution treated for 4 hr at 1040° C (1900 °F) and oil quenched. The high temperature heat treatment of 1040 °C (1900°) was used instead of the nominal 1020 °C (1865 °F) of AMS 5704C to maintain the same difference between the γ' solvus and the heat treatment temperature as with AMS 5704C material. Subsequent aging treatments of 4 hr at 845 °C (1550 °F) and 16 hr at 760 °C (1400 °F) both followed by air cooling are as specified in AMS 5704C.

Results and Discussion

Forgings were evaluated by four gas turbine manufacturers, Allison Gas Turbine Division, Garrett Turbine Engine Company, Lycoming, and Rocketdyne. NASA provided the forgings to the gas turbine manufacturers to evaluate as they wished. In addition, Wyman Gordon tested two forgings for comparison with the mechanical property requirements of AMS 5704C.

Metallographic Examination

Typical photomicrographs of the web and rim regions of a forging are shown in figures 2(a) and (b). The grain size was typically ASTM 5 to 7, however occasional grains as coarse as ASTM 3 and fine as ASTM 9 were observed. In addition to the metallography to determine the grain size, scanning electron microscopy was performed at the Lewis Research Center on samples taken from two forgings. A representative scanning electron micrograph is shown in figure 3. The grain boundaries are decorated with a fine discontinuous phase which was determined to be enriched with chromium. It is assumed to be an $M_{23}C_6$ carbide. Shown in the triple point of figure 3 is a titanium rich phase which is surrounded by γ'(dark region). The Ti rich phase, which also contained Mo, is assumed to be an MC carbide. There appears to be a relatively uniform dispersion of about 10 vol % γ' with a nominal diameter of about 0.15 µm. In addition, more massive γ' can be seen adjacent to carbides.

Tensile Tests

Tensile tests were performed between room temperature and 760 °C (1400 °F). The effect of temperature on the tensile ultimate and yield strengths of low cobalt Waspaloy are summarized in figure 4. The data points shown are the average for each laboratory which typically performed either duplicate or triplicate tests. The error bars show 1 standard deviation. Where no error bar is shown, the standard deviation is smaller than the data point symbol. The average line was determined by regression using a fourth order polynomial for all the data. The R^2 was 0.99 for the ultimate strength and 0.92 for the yield strength. The average line is biased toward the results of laboratory 1 because it provided more data points than the other labs. The data is generally in good agreement and significantly greater than the AMS minimum values for both ultimate and yield strengths at room temperature and 540 °C (1000 °F).

The effect of temperature on the ductility of low cobalt Waspaloy is summarized in figure 5 The curves are the result of regression using a third order equation for all data. For clarity only negative error bars are shown in figure 5. The R^2 for the reduction in area is 0.75 and for the elongation is 0.58. The average room temperature and 540 °C (1000 °F) values are significantly greater than the AMS 5704C minimum values of 18 percent reduction in area and 15 percent elongation. However, one 540 °C (1000 °F) test performed by Wyman Gordon (Lab 4) had a reduction in area of only 13 percent, which is below the 18 percent minimum required by AMS 5704C. That test location was near the rim of the forging and it is believed, but not verified, that there were a few very large grains in the test bar.

Creep Rupture Tests

Creep rupture tests were performed at temperatures from 620 to 895 °C (1145 to 1640 °F) and stresses from 758 to 138 MPa (110 000 to 20 000 psi) with the highest stresses being associated with the lowest temperature. A Larson-Miller master plot of the stress rupture life of low cobalt Waspaloy is shown in figure 6. The data for all the forgings is in good agreement. The average curve shown in figure 6 is a regression using a second order equation for all data. The data points represent individual tests. The handbook curve shown is also a regression using a second order equation of data from the Aerospace Structural Metals Handbook.[6] The R^2 for both curves was greater than 0.99. While the average data was greater that the AMS 5704C minimum values, it can be seen that several data points were only slightly greater in value than the specified minimums. At higher stress (low temperature) levels, above about 414 MPa (60 Kpsi), the low cobalt Waspaloy was in good agreement with the Larson Miller Parameter values from reference 6. But at the lower stress (higher temperature) levels the low cobalt Waspaloy data appears to fall below the handbook data. The reduced performance of the low cobalt alloy at the higher temperatures is believed to be caused by the presence of grains as fine as ASTM 8 to 9 in the forgings.

Figure 7 is a Larson-Miller master plot of 1 percent creep data. Only 2 laboratories chose to obtain creep data. As above, the curves are second order equation regressions of the data. They had R^2's in excess of 99 percent. The trends observed for the rupture data also exist for the creep data. In the high stress region (above about 552 MPa (80 Kpsi)) the low cobalt Waspaloy and the handbook data are comparable, but at lower stresses the handbook values have greater Larson-Miller Parameters than the low cobalt Waspaloy.

Low Cycle Fatigue

Strain controlled low cycle fatigue (LCF) tests were performed by three laboratories. The test temperatures were from 425 to 650 °C (800 to 1200 °F). Tests were performed at R ratios of 0.0 and -1.0 with total strain-ranges from 0.5 to 2.5 percent. The data for 425 and 480 °C (800 and 900 °F) are shown in figure 8 and data for 595 and 650 °C (1100 and 1200 °F) are shown in figure 9. The curve shown in each figure is for Lab 1's R = -1.0 data. Data for other tests at differing R ratios and temperatures are shown without curves for clarity. As expected, the R = 0.0 data falls below the R = -1.0 data at lower strain-ranges and there is only a small temperature sensitivity over the temperature range studied. The agreement between forgings evaluated at different laboratories is excellent. The LCF behavior of the low cobalt Waspaloy is similar to that reported by Pratt & Whitney Aircraft.[7,8]

Load controlled LCF tests were performed at 425 and 595 °C (800 and 1100 °F) by one laboratory. The results are shown in figure 10.

Cyclic Crack Growth

Cyclic crack growth data was obtained by two laboratories for temperatures ranging from 425 to 650 °C (800 to 1200 °F). The data is summarized in figure 11. The crack growth behavior at 650 °C (1200 °F) was reported by laboratory 2 to be similar to that expected for standard Waspaloy with a grain size of ASTM 6.

Hydrogen Environment Embrittlement

One laboratory chose only to evaluate the effects of hydrogen on the room temperature tensile properties of the low cobalt alloy.

The tests were performed in triplicate in 103 MPa (15 000 psi) helium or hydrogen. The notched specimens had a k_t of 6.3. The tensile strength results are summarized in figure 12 and the ductility results are summarized in figure 13. The He results compare well with those performed in room temperature air shown in figures 4 and 5. Comparing the smooth and notched ultimate strength in hydrogen and in helium it is apparent that the alloy's ultimate strength is degraded by the hydrogen environment. The yield strength was not significantly affected by the hydrogen. The ratio of the ultimate strength in hydrogen to the ultimate strength in helium is 0.83 for smooth bars and is 0.65 for notched bars. Corresponding values for reduction in area and elongation degradation in hydrogen compared to helium are 0.22 and 0.26. The laboratory which performed the tests reported that these values are similar to the lower bound of data they have obtained for Waspaloy. Based on these results the low cobalt alloy does not appear to be attractive for service in high pressure hydrogen.

Summary and Conclusions

The mechanical properties of a 1365 kg (3000 lb) heat of low cobalt Waspaloy which was forged to a disk-like shape was evaluated. The alloy had about one half of the normal cobalt and slightly greater aluminum and titanium than AMS 5704C Waspaloy. The evaluation by four gas turbine manufacturers and Wyman Gordon included tensile testing from room temperature to 760 °C (1400 °F), creep rupture life, low cycle fatigue life and cyclic crack growth tests. Except for lower creep and rupture lives at lower stresses (higher temperatures), the mechanical properties compared well with published values for standard Waspaloy. The AMS specified values for strength, ductility (except for one reduction in area value) and rupture life were exceeded where comparable tests were performed.

It is concluded that in the event of a cobalt shortage, a low cobalt modification of Waspaloy could be substituted for standard Waspaloy with little development in those applications which are not creep rupture limited. With some additional development to better control grain size, it is probable that most of the current Waspaloy requirements might be met with a lower cobalt alloy.

Acknowledgment

The author gratefully acknowledges the contributions of M.A. Khan, Shahid Bashir and Mehmet Doner of Allison Gas Turbine Division, George Hoppin, III of Garrett Turbine Engine Company, Lou Fiedler of Textron Lycoming, and Jon Frandsen of Rocketdyne for performing the tests and providing the data for this report. J. Saltzman of the Lewis Research Center assisted in analyzing the low cycle fatigue data.

References

1. Joseph R. Stephens, Resources-Supply and Availability, Superalloys, Supercomposites and Superceramics, J.K. Tien ed., Academic Press, Inc., 1989, p 9 ff.

2. G.E., Maurer, L.A., Jackman, and Dominque, Role of Cobalt in Waspaloy, Superalloys 1980, J. K. Tien et al. eds., ASM, 1980, p 43 ff.

3. Robert N. Jarrett, N. Robert and John K. Tien, Effects of Cobalt on Structure, Microchemistry and Propertes of a Wrought Nickel-Base Superalloy., Met. Trans.A, Vol. 13A, 1982, p 1021 ff.

4. William J. Jr. Durako, The Role of Cobalt in Waspaloy, Purdue University, December 1981.

5. Aerospace Materials Specifications, Society of Automotive Engineers, Warrendale, PA.

6. Aerospace Structural Metals Handbook, Metals and Ceramics Information Center, Columbus, OH, Sept. 1986, code 4208.

7. B.A. Cowles, D.L. Sims, and J.R. Warren, Evaluation of the Cyclic Behavior of Aircraft Turbine Disk Alloys, NASA CR-159409, Pratt & Whitney Aircraft, W. Palm Beach, FL, 1978.

8. B.A. Cowles, J.R. Warren, and Haake, Evaluation of the Cyclic Behavior of Aircraft Turbine Disk Alloys, Part II, NASA CR-165123, Pratt & Whitney Aircraft, W. Palm Beach, FL., 1980.

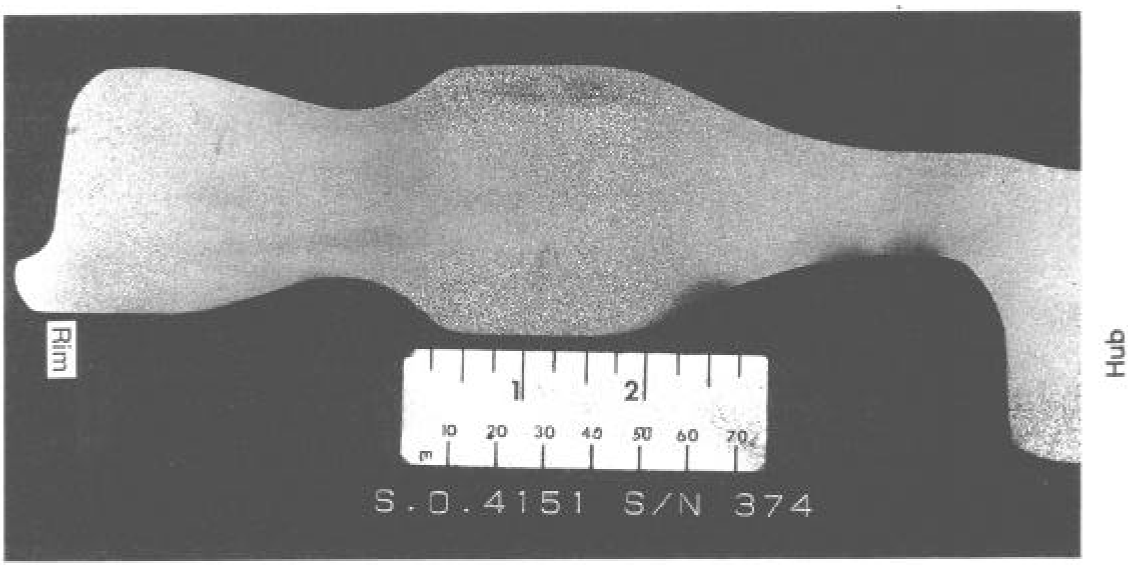
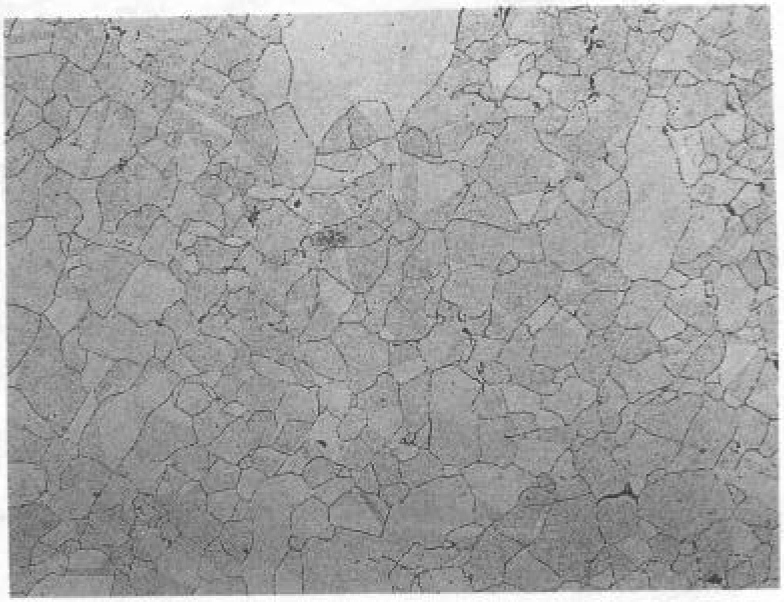
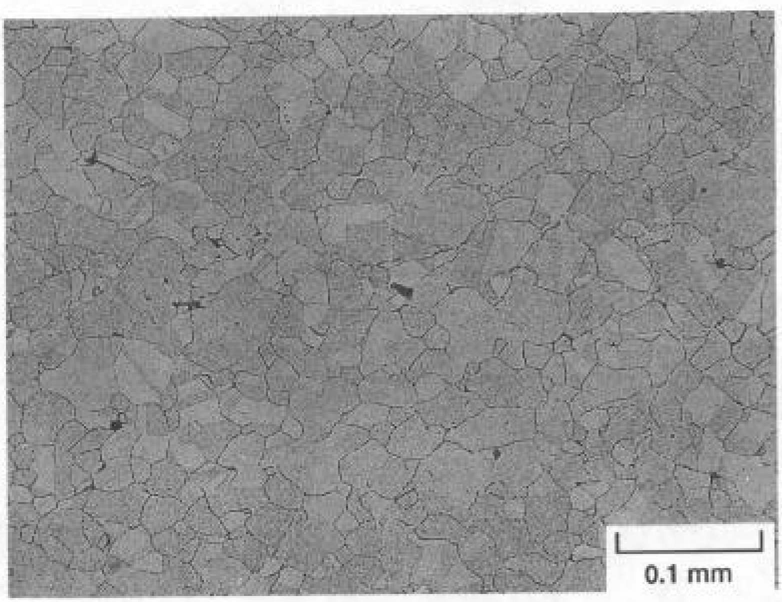


Figure 1.—Low cobalt waspaloy forging.



(a) Rim.



(b) Web.

Figure 2.—Typical photomicrograph of low cobalt waspaloy.

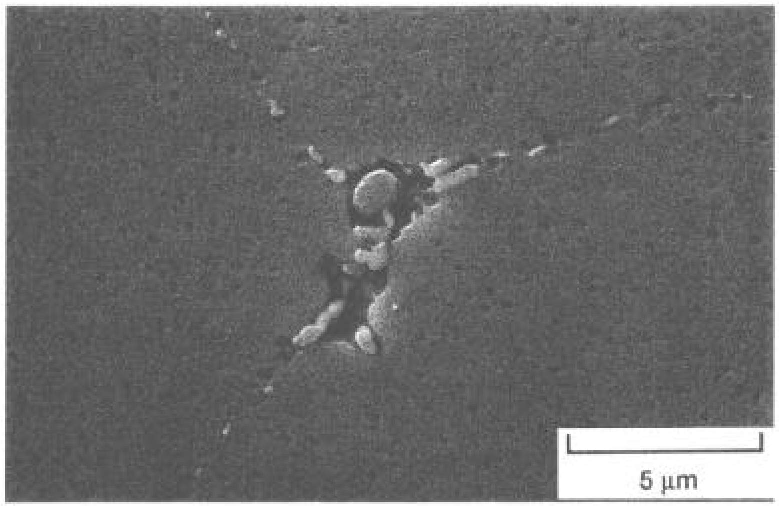


Figure 3.—Scanning electron micrograph of low cobalt waspaloy.

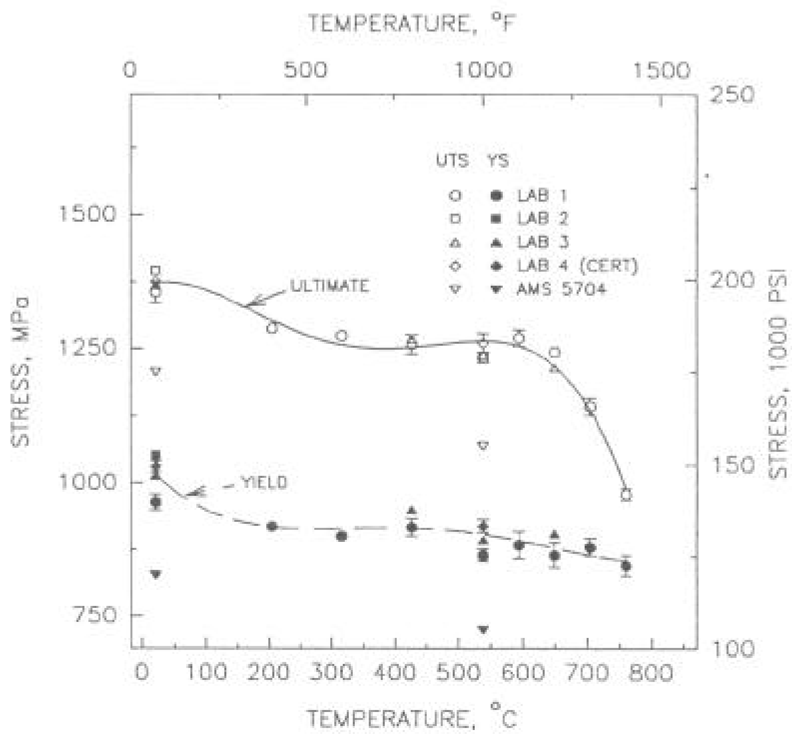
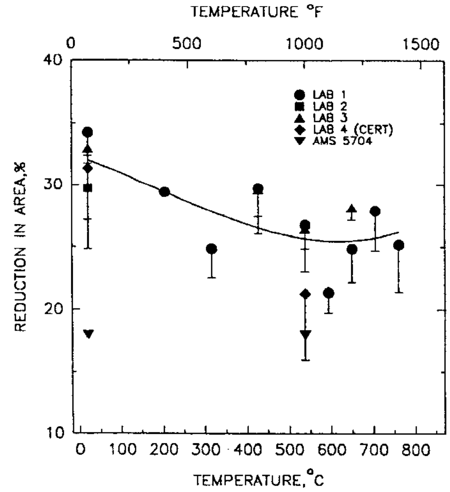
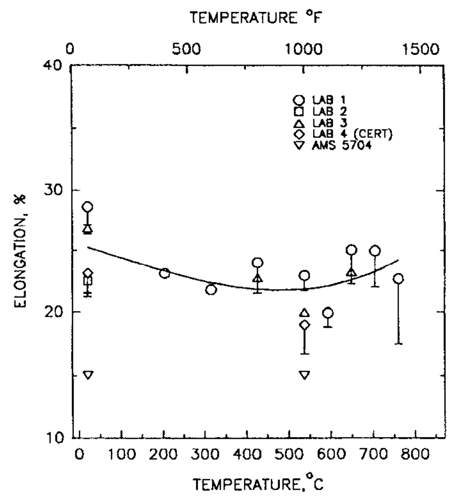


Figure 4.—Effect of temperature on the strength of low cobalt waspaloy.

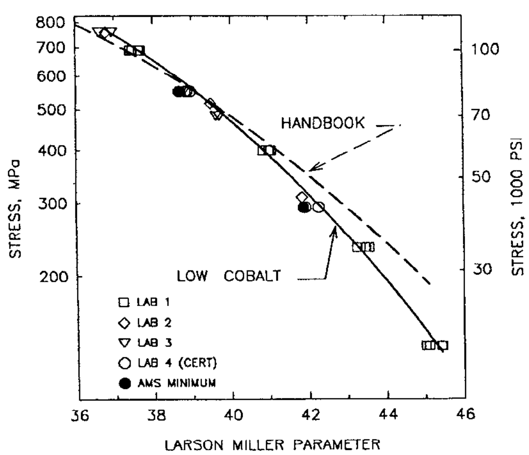


(a) Reduction in area.



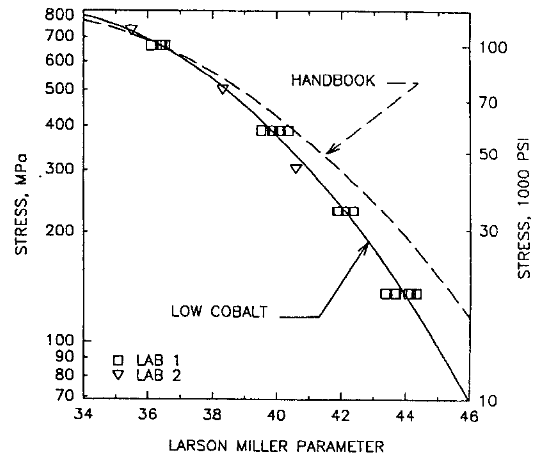
(b) Elongation.

Figure 5.—Effect of temperature on the ductility of low cobalt waspaloy.



P = (1.8 K(20 + Log t))/1000

Figure 6.—Stress rupture of low cobalt waspaloy.



P = (1.8 K(20 + Log t))/1000

Figure 7.—One percent creep of low cobalt waspaloy.

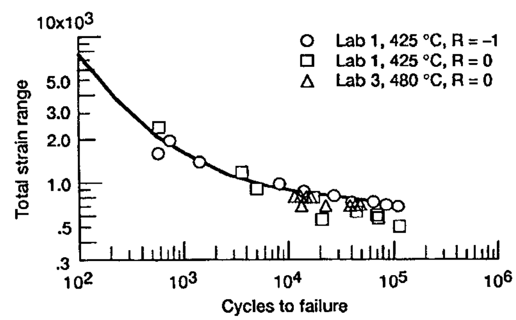


Figure 8.—Low cycle fatigue behavior of low cobalt waspaloy at 425 and 480 °C.

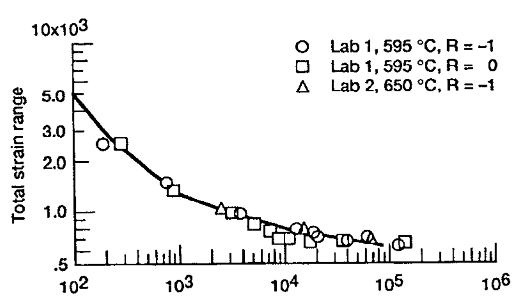


Figure 9.—Low cycle fatigue behavior of low cobalt waspaloy at 595 and 650 °C.

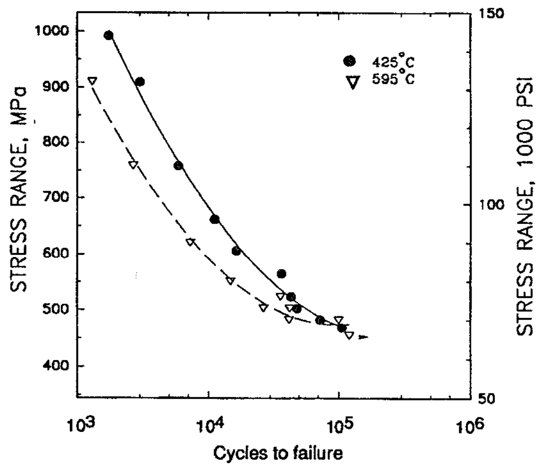


Figure 10.—Load controlled low cycle fatigue of low cobalt waspaloy.

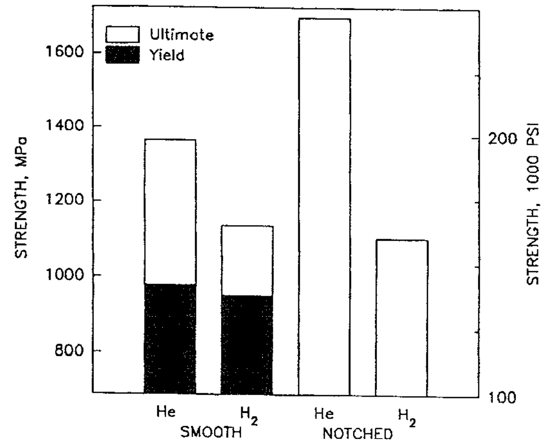


Figure 12.—Effect of high pressure H_2 on the tensile strength of low cobalt waspaloy.

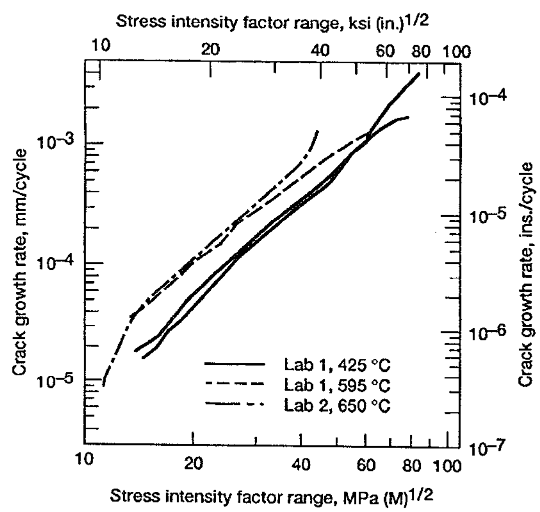


Figure 11.—Cyclic crack growth behavior of low cobalt waspaloy.

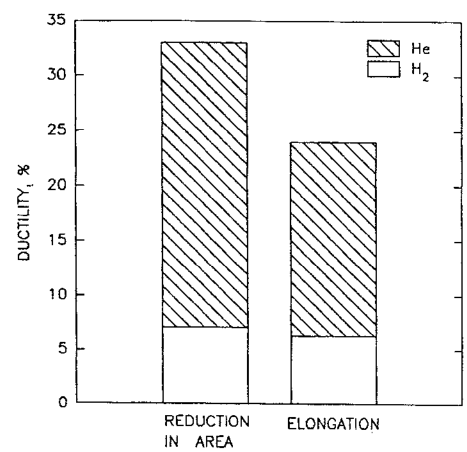


Figure 13.—Effect of high pressure H_2 on the dutility of low cobalt waspaloy.