Evaluation of Mechanical Properties of a Low-Cobalt Wrought Superalloy

R.L. Dreshfield

In the late 1970s and early 1980s, 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 Conservation of Strategic Aerospace Materials (COSAM) 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 minimal 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 article 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 cobalt 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% and the titanium was increased from 3.0 to 3.2%. The increase in aluminum and titanium 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 was concluded that, in the event of a cobalt shortage, a low-cobalt modification of Waspaloy alloy could be substituted for Waspaloy with little development in those applications that 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.

Keywords
cobalt-base, mechanical properties, superalloy, turbine blade materials

1. Introduction

IN the late 1970s and early 1980s, 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—cobalt, chromium, niobium, and tantalum—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 3-year life of the COSAM program, considerable progress was made in understanding the effects of cobalt on the properties of several nickel-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 article.

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1.1 *Alloy Selection and Processing*

Based on previous work performed at Special Metals,[2] Columbia University,[3] Purdue University,[4] and private communication with Professor J. 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 1. The nominal level of cobalt was reduced from 13.5 to 7.75 wt%, and titanium and aluminum were increased from 3.0 and 1.3 to 3.2 and 1.5%, respectively. The increase in titanium and aluminum were intended to compensate for the slight loss in the amount of γ' expected from the increase in nickel resulting from the changes.

A 1365-kg (3000-lb) vacuum induction melted vacuum arc remelted (VIM/VAR) 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 h at 1205 °C (2200 °F). The ingot was drawn to 28 cm (11 in.) diameter at 1190 °C (2175 °F) and finished at

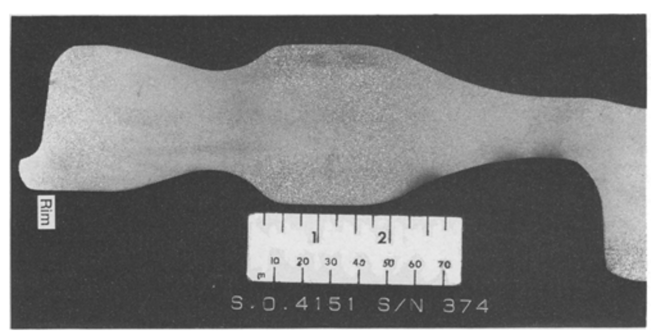


Fig. 1 Low-cobalt Waspaloy forging.

23 cm ($8\frac{7}{8}$ in.) diameter at 1160 °C (2125 °F). The billet was then ground to 20 cm (8 in.) diameter and contact sonic inspected to a No. 3 flat-bottom hole. The billet was cut to 22 cm (8.5 in.) long and 56 kg (123 lb) forging multiples that were upset at 1110 °C (2025 °F) in a 9100-kg (20,000-lb) hammer forge and finished at 1095 °C (2000 °F) in a 16,000-kg (35,000-lb) hammer to the disk shape shown in Fig. 1. Eight forgings were made.

The γ' solvus temperature was determined by differential thermal analysis (DTA) to be 1058 °C (1937 °F). The forgings were solution treated for 4 h at 1040 °C (1900 °F) and oil quenched. The high-temperature heat treatment of 1040 °C (1900 °F) 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 h at 845 °C (1550 °F) and 16 h at 760 °C (1400 °F), both followed by air cooling, were as specified in AMS 5704C.

2. Results and Discussion

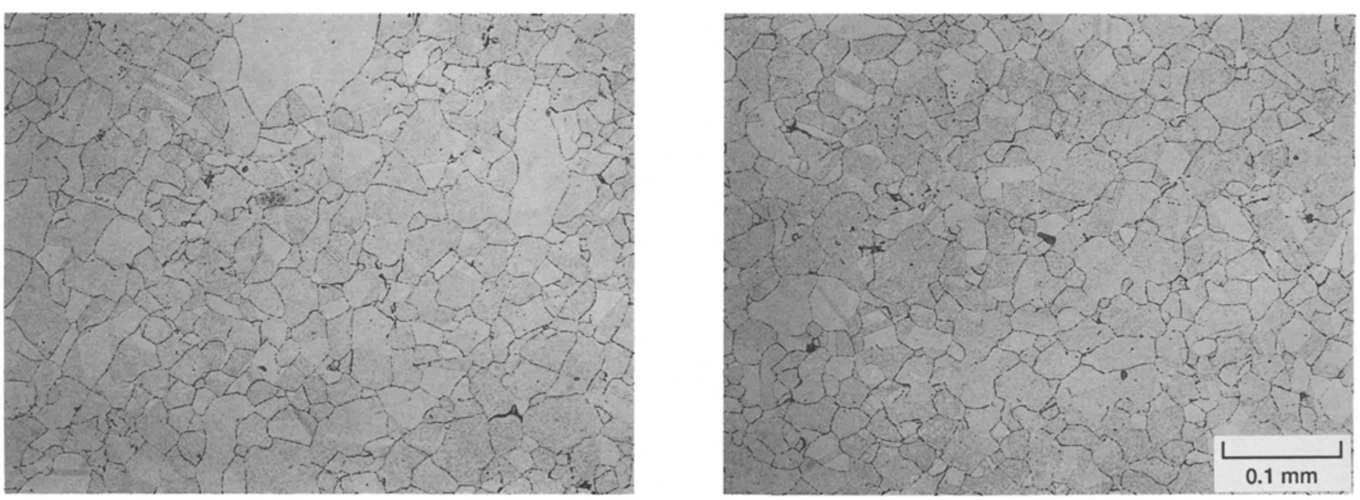
Forgings were evaluated by four gas turbine manufacturers—Allison Gas Turbine Division, Garrett Turbine Engine Company, Lycoming, and Rocketdyne. NASA provided the forgings to the gas turbine manufacturers to evaluate as they wished. In addition, Wyman Gordon tested two forgings for comparison with the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

2.1 *Metallographic Examination*

Typical photomicrographs of the web and rim regions of a forging are shown in Fig. 2(a) and (b). The grain size was typically ASTM 5 to 7, however, occasional grains as coarse as ASTM 3 and as fine as ASTM 9 were observed. In addition to the use of metallography to determine grain size, scanning electron microscopy (SEM) was performed at the Lewis Research Center on samples taken from two forgings. A representative scanning electron micrograph is shown in Fig. 3. The grain boundaries are decorated with a fine discontinuous phase, which was determined to be enriched with chromium. It was assumed to be an $M_{23}C_6$ carbide. Shown in the triple point of Fig. 3 is a titanium-rich phase that is surrounded by γ' (dark region). The titanium-rich phase, which also contained molybdenum, was 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. Additionally, more massive γ' is adjacent to the carbides.

Table 1 Composition of alloys

Element	Composition, wt% AMS 5704C Minimum	AMS 5704C Maximum	Low-cobalt Waspaloy Minimum	Low-cobalt Waspaloy 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



(a) (b)

Fig. 2 Typical photomicrograph of low-cobalt Waspaloy. (a) Rim. (b) Web.

2.2 *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 is summarized in Fig. 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 of 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 laboratories. The data are 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).

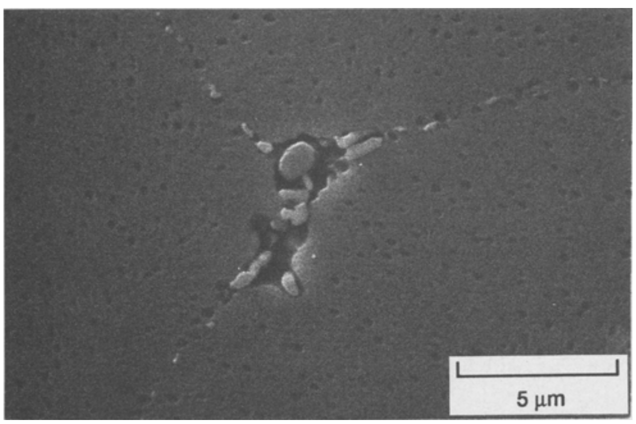


Fig. 3 Scanning electron micrograph of low-cobalt Waspaloy.

The effect of temperature on the ductility of low-cobalt Waspaloy is summarized in Fig. 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 Fig. 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% reduction in area and 15% elongation. However, one 540 °C (1000 °F) test performed by Wyman Gordon (Labora-

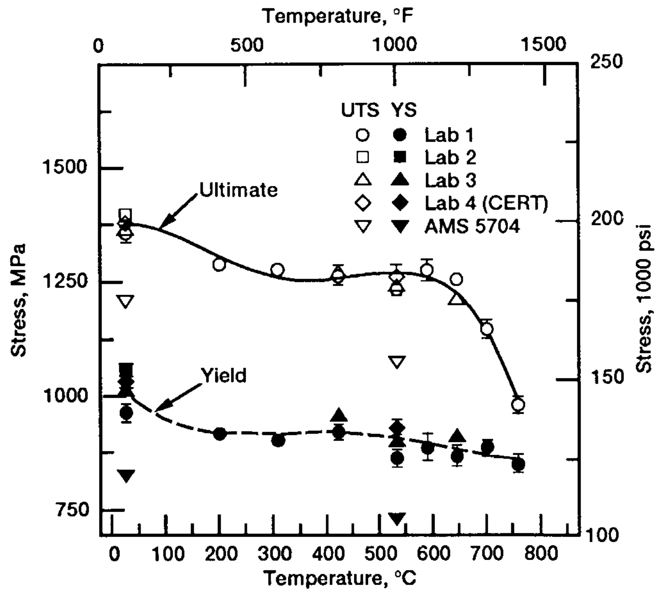


Fig. 4 Effect of temperature on the strength of low-cobalt Waspaloy.

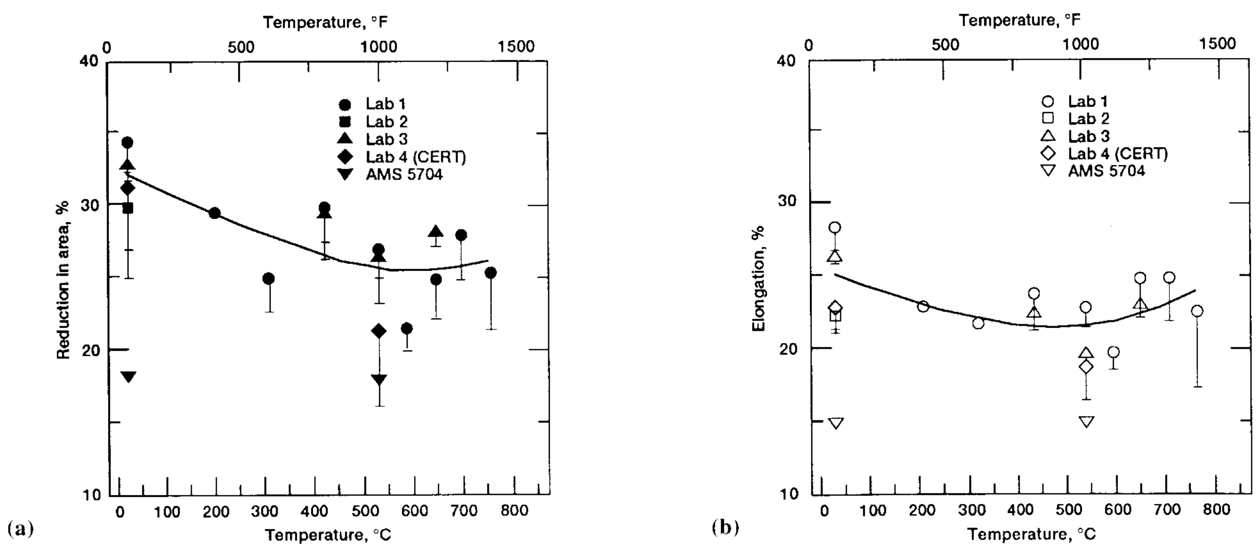


Fig. 5 Effect of temperature on the ductility of low-cobalt Waspaloy. (a) Reduction in area. (b) Elongation.

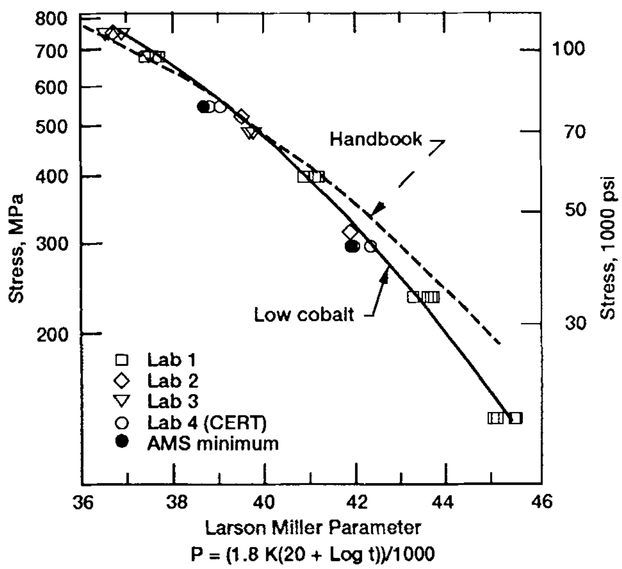


Fig. 6 Stress-rupture of low-cobalt Waspaloy.

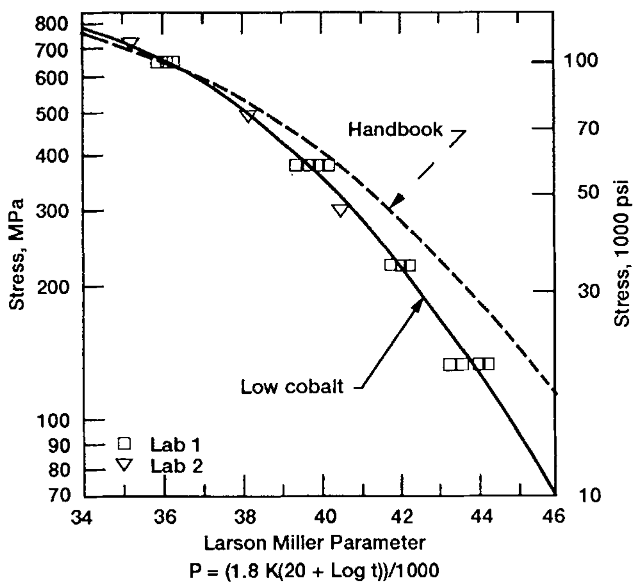


Fig. 7 1% creep of low-cobalt Waspaloy.

tory 4) had a reduction in area of only 13%, which is below the 18% minimum required by AMS 5704C. That test location was near the rim of the forging, and it was believed, but not verified, that there were a few very large grains in the test bar.

2.3 *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 Fig. 6. The data for all the forgings are in good agreement. The average curve shown in Fig. 6 is a regression using a second-order equation for all of the 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. Although the average data were greater than the AMS 5704C minimum values, several data points were only slightly greater in value than the specified minimums. At higher stress (low temperature) levels, above about 414 MPa (60 ksi), the low-cobalt Waspaloy was in good agreement with the Larson-Miller parameter values from Ref 6. However, at the lower stress (higher temperature) levels, the low-cobalt Waspaloy data appear 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% creep data. Only two laboratories chose to obtain creep data. As above, the curves are second-order equation regressions of the data. They had R^2 values in excess of 99%. The trends observed for the rupture data also exist for the creep data. In the high-stress region (above about 552 MPa (80 ksi)), 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.

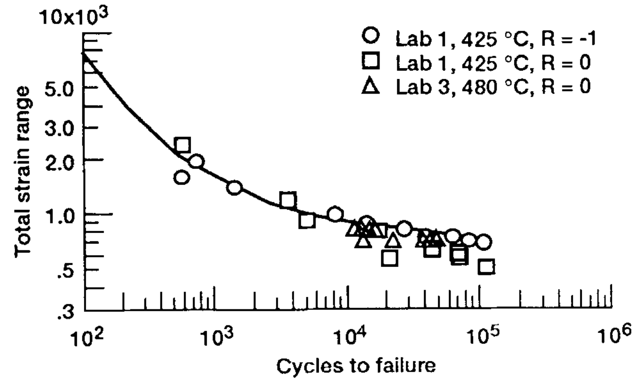


Fig. 8 Low-cycle fatigue behavior of low-cobalt Waspaloy at 425 and 480 °C.

2.4 *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%. The data for 425 and 480 °C (800 and 900 °F) are shown in Fig. 8, and data for 595 and 650 °C (1100 and 1200 °F) are shown in Fig. 9. The curve shown in each figure is for the $R = -1.0$ data of Laboratory 1. Data for other tests at differing R ratios and temperatures are shown without curves for clarity. As expected, the $R = 0.0$ data fall below the $R = -1.10$ 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]

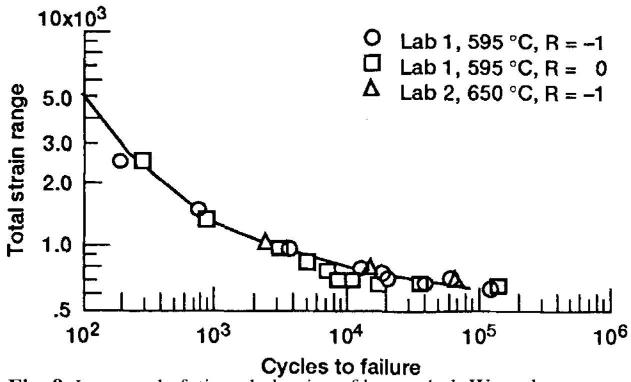


Fig. 9 Low-cycle fatigue behavior of low-cobalt Waspaloy at 595 and 650 °C.

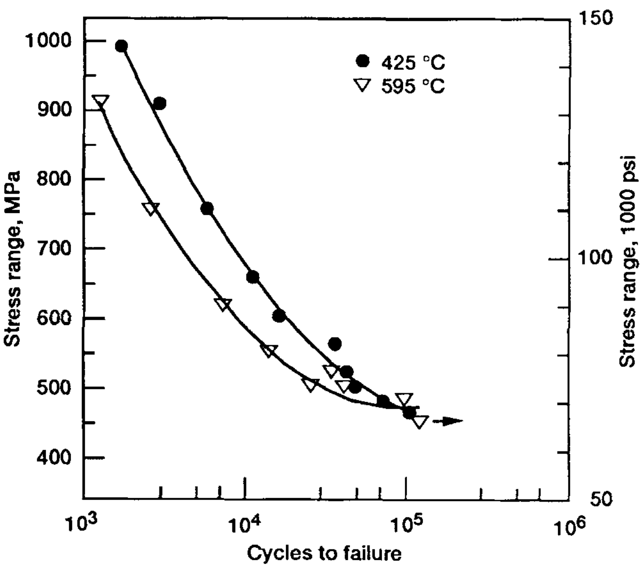


Fig. 10 Load-controlled low-cycle fatigue of low-cobalt Waspaloy.

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

2.5 *Cyclic Crack Growth*

Cyclic crack growth data were obtained by two laboratories for temperatures ranging from 425 to 650 °C (800 to 1200 °F). The data are summarized in Fig. 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.

2.6 *Hydrogen Embrittlement*

One laboratory chose to evaluate only 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 Fig. 12, and the ductility results are summarized in Fig. 13. The helium

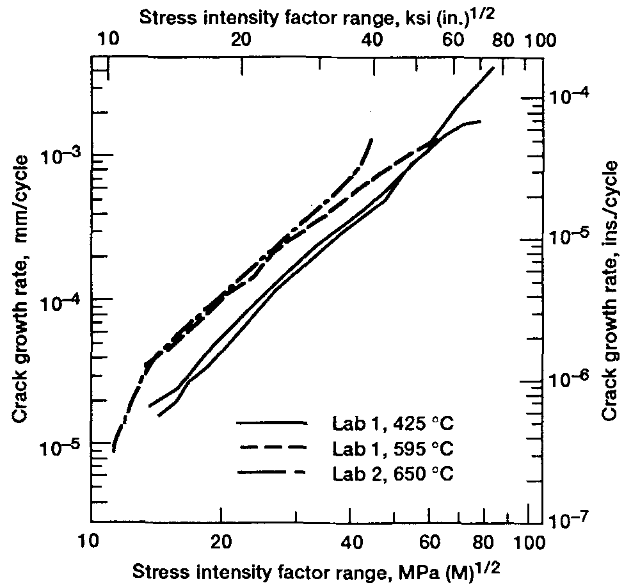


Fig. 11 Cyclic crack growth behavior of low-cobalt Waspaloy.

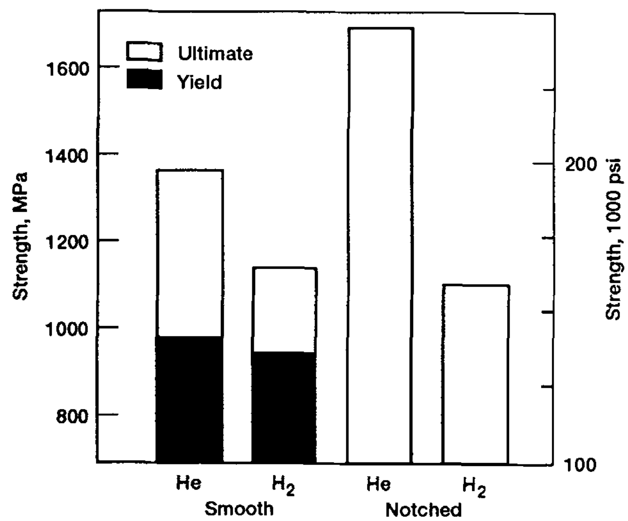


Fig. 12 Effect of high-pressure hydrogen on the tensile strength of low-cobalt Waspaloy.

results compare well with those performed in room-temperature air shown in Fig. 4 and 5. Comparing the smooth and notched ultimate strength in hydrogen and in helium, it is apparent that the ultimate strength is degraded by the hydrogen environment, whereas 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 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 that performed the tests reported that these values are similar to the lower bound of data obtained for Waspaloy. Based on these results, the low-cobalt alloy does not appear to be attractive for service in high-pressure hydrogen.

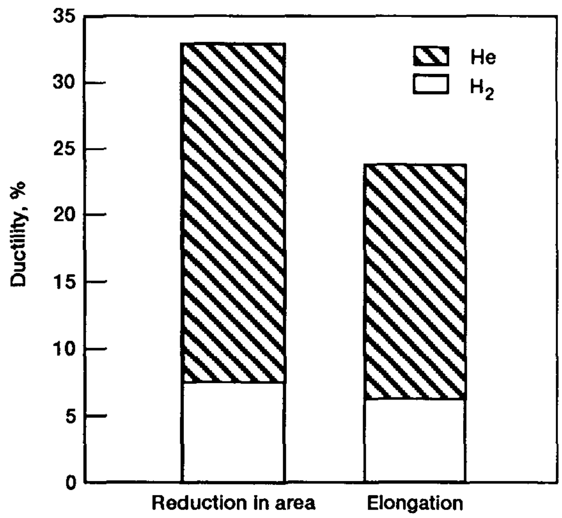


Fig. 13 Effect of high-pressure hydrogen on the ductility of low-cobalt Waspaloy.

3. Summary and Conclusions

The mechanical properties of a 1365-kg (3000-lb) heat of low-cobalt Waspaloy that 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 minimal development in those applications that 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.

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