NASA Technical Memorandum 107191

Long Time Creep Rupture of Haynes™ Alloy 188

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Corrected Copy

Prepared for the
Eighth International Symposium on Superalloys
sponsored by The Minerals, Metals, and Materials Society
Champion, Pennsylvania, September 22–26,1996

National Aeronautics and
Space Administration

LONG TIME CREEP RUPTURE OF HAYNES^{TM} ALLOY 188

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Abstract

The creep of Haynes Alloy 188 sheet in air was studied at temperatures of 790°, 845° and 900 °C for times in excess of 30,000 h as part of a program to assure that Haynes Alloy 188 could be used in critical components of a solar dynamic power conversion system for Space Station Freedom. The rupture life and time to 0.5 and 1.0 percent creep strain of creep rupture specimens which had lives from about 6,000 to nearly 59,000 h are reported. Both welded and as-received specimens were tested. The welded specimen had essentially the same lives as the as-received specimens. Comparison of this data with previously published results suggests that this material was similar in behavior to that previously studied by Haynes except at 790 °C where the current sheet is somewhat stronger in stress rupture. Therefore the previously published data for Haynes Alloy 188 may be used in conjunction with this data to estimate the lives of components for a long life solar dynamic power system.

Three creep rupture tests were discontinued after 16,500 to 23,200 h and tensile tested at room temperature or 480 °C. The elongation of all three specimens was substantially reduced compared to the as-received condition or as aged (without applied stress) for 22,500 h at 820 °C. The reduction in elongation is thought to be caused by the presence oxidized pores found across the thickness of the interrupted creep specimens. The implications of the severe loss of ductility observed in tensile tests after prolonged creep test needs further study.

Introduction

A solar dynamic power conversion system was planned for Space Station Freedom to provide additional electrical power to the space station as it grew.[1] Solar dynamic power systems are designed to convert solar energy to electric energy using heat engines. A schematic diagram of a space-based solar dynamic power system in shown in Fig. 1.

One component of the power conversion system (the receiver) both receives the solar energy for use while it is exposed to solar radiation and stores the energy as latent heat of fusion in molten salt to provide energy while the space station is in the shadow of Earth. The material chosen for some of the critical parts of the receiver, including the salt containment canisters and hot gas manifold, was Haynes alloy188.[2]

Because Space Station Freedom was to be designed for a 30 year life, with only one replacement of the power module, long term creep rupture data was required to validate the designs of those critical parts. Review of available data failed to identify data in the appropriate temperature range exceeding 10,000 h. Since the design life would be for 260,000 h, it was necessary to acquire data for times for at least 26,000 h to assure the design, initially based on the existing data, would meet durability goals.

The work reported here was initiated to provide such data. A limited study was conducted to evaluate the creep rupture behavior of 1.3 mm thick Haynes Alloy 188 at 790° and 845 °C for times varying from 10,000 to 30,000 h. The 10,000 h data was intended to provide a link with existing data[3] while the high time data would be about 10 percent of the target life. Both as-received and welded material were evaluated. During the course of the work a few tests at 900 °C were substituted for some of the lower temperature tests. Time to 0.5 and 1.0 percent creep and rupture properties were determined.

Materials And Test Methods

The material tested was from a single heat of Haynes Alloy 188 in the bright annealed, solution treated condition which had previously been procured to study the effects of long time molten salt and elevated temperature vacuum exposures on the alloy.[2,4,5] The sheet had a nominal thickness of 1.4 mm. The composition as provided by the vendor was: 0.11 C, 0.72 Mn, 0.38 Si, 21.69 Cr, 23.03 Ni, 1.95 Fe, 14.02 W, 0.048 La, 0.002 S, 0.13 P, and the balance Co. It was reported by the vendor to have a grain size of ASTM No. 6.5.

The test specimens which were machined from the sheets had a gage section 9.5 mm wide and 55 mm long. They were pin loaded using 6.4 mm diameter pins 12.8 cm on centers. The overall length of the specimen was 16.5 cm. V grooves about 0.05 mm deep were machined into one side of the specimen in a 15.9 mm wide shoulder to minimize slippage of knife edge extensometers. The welded samples were tungsten inert gas welded (TIG), using sheet material as starter stock, such that the weld was in the center of the gage section. After welding, the starter tabs were removed and the weld was blended to be smooth with the base metal surfaces. The thickness of the welds were typically about 5 percent greater than the base metal. No post-weld heat treatment was performed.

Creep rupture tests were performed in air on constant load frames. Loads were based on extrapolation of existing data[3] for failure times from 10,000 to 30,000 h at temperatures of 790° and 845 °C. Because of concern for higher temperature excursions in the receiver, a few shorter duration tests were initiated at 900 °C. For the lightest loads, direct loading was used, while for other tests lever arm machines

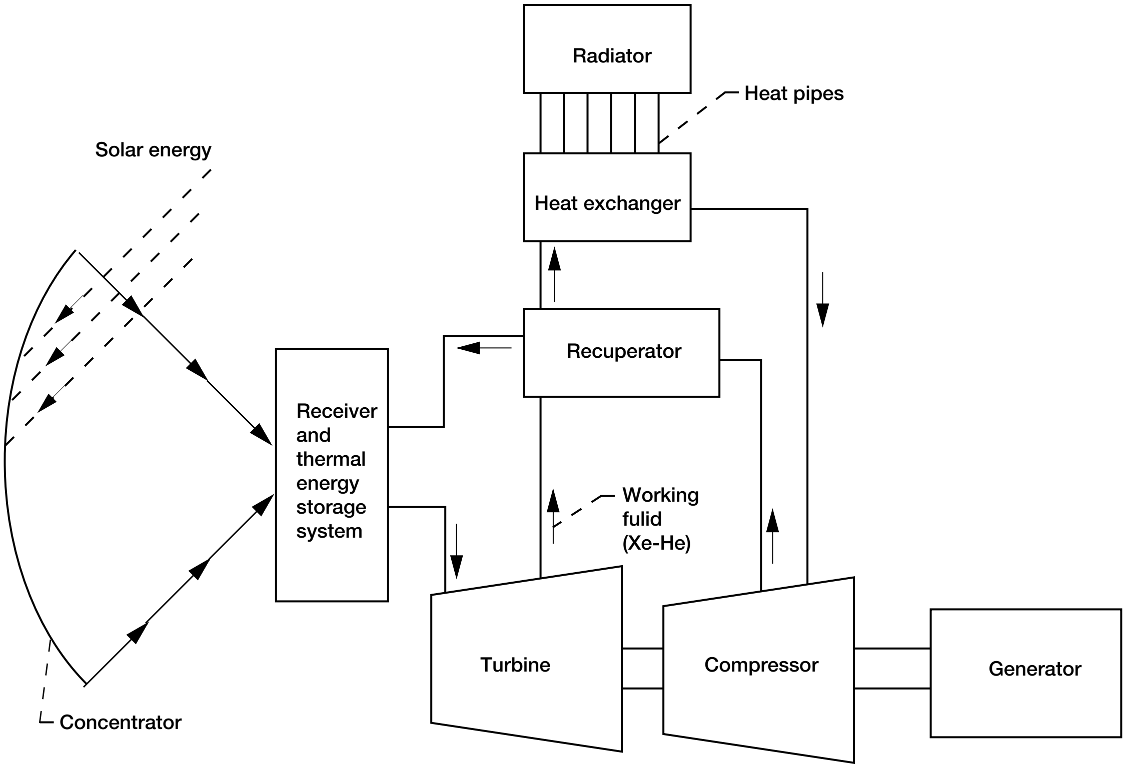

Figure 1.—Schematic representation of space based solar dynamic power system. (ref. 3).

having lever ratios from 4:1 to 20:1 were used. Deformation was measured using an extensometer with a LVDT transducer. All of the extensometer motion was assumed to occur in the gage section. The data was recorded using a PC based data acquisition system. The resolution of the creep measurement was approximately 0.01 percent. Recording time was typically set at 24 to 36 h increments for most of the test. Shorter times were used during the first few days of the tests.

Three tensile tests on creep exposed specimens were performed using a screw loaded testing machine. Initial strain rate was controlled by using a constant crosshead speed equivalent to 0.0016 percent strain per second. Extension was measured using an extensometer with a 12.7 mm gage length.

Results And Discussion

Creep-Rupture Tests

The test matrix and results are shown in Table I. The creep-rupture results are summarized in Fig.2(a). The data with arrows were discontinued to make the test frames available for another program and were subsequently tensile tested. "H" represents our estimate of 10,000 h life based on the Tackett[3] data. The lines are 1st order regression lines of the experimental data. Figure 2(a) shows that the time to rupture at 845° and 900° are in good agreement with the expectation derived from Tackett's work. At the lowest temperature studied, 790°, the material in this study appears to be somewhat stronger than that studied by Tackett.

It should be noted that the material studied by Tackett was in the black annealed, pickled and stretcher leveled condition and the current material was provided in the bright annealed condition. A private communication with Mr. M. Rothman of Haynes Alloys International revealed that the strain introduced by stretcher leveling has the potential to improve the lower temperature creep rupture strength. This was not observed in this study.

The stress rupture data at 790° and 850 °C are presented in Fig.2(b) with the as-received material identified as the open symbols and the welded alloy identified as the filled symbols. The presence of the welds did not appear to have a significant effect on the rupture life, and this is borne out by visual examination of the failures (Fig. 3). None of the welded samples failed in the weld. However as the welds were typically 5 percent thicker, with some up to 10 percent, it is possible that the weld could be up to 10 percent weaker than the base metal without reducing the lives of the specimens.

The same heat of material used in this investigation was also used by Whittenberger.[2,4,5] He performed stress rupture tests in vacuum at 775° at stresses to produce failure in 10 to 1000 h. The 790° data from this study are compared to his data in Fig. 2(c). While the linear extrapolations of each data set show some deviation, the data are in reasonable agreement. One might expect some curvature in isothermal rupture curves with the lower stress tests failing at somewhat shorter times than expected from extrapolation of the higher stress data.

Both elongation and reduction in area (RA) are presented for the failed Haynes Alloy 188 stress rupture specimens in Table I. At the two lower temperatures the elongations varied from 15 to 30 percent without any apparent dependence on the initial applied stress. At 900 °C the elongations varied from 67 to 96 percent which are significantly greater than those measured at the lower temperatures. Comparison of the elongations for the welded to the as-received indicates a tendency for somewhat less elongation for the welded specimens. For example at 845 °C-42 MPa the two as-received samples had elongations of 19.5 and 21.5 percent while the two welded samples had elongations of 21.5 and 12 percent. Similar behavior can be seen at 51 MPa. It is

Table I Creep Test Matrix

Stress, MPa	Temper-ature, ˚C	Weld	0.5% creep h	1% creep, h	Elong., %	Red. in Area, %	Rupture Life, h
74	790	N	760	5620	23.5	11.3	58664
74	790	N	1380	6170	NA.	NA.	[d]23230
77	790	N	360	1980	14.5	12.9	48476
77	790	N	103	401	NA.	NA.	[d]16518
86	790	N	190	1190	20.5	12.8	31288
86	790	N	90	5400	19.5	12.9	26386
103	790	N	50	216	22.5	18.3	13441
42	845	N	1400	7480	19.5	6	27968
42	845	N	1480	8340	21.5	9.8	31213
42	845	Y	2400	10300	22	6.8	33370
42	845	Y	4940	12230	12.5	4.5	28540
44	845	N	1660	11290	30.5	10.3	39950
44	845	N	400	3300	23	11.3	26250
44	845	Y	NA.	NA.	21.5	13.1	21473
44	845	Y	1800	6307	NA.	NA.	[d]22115
51	845	N	1035	4860	23	10	18814
51	845	Y	720	3830	22.5	12.4	24111
51	845	N	870	2600	30.5	10.3	13940
51	845	Y	816	3200	15	10.9	15860
28	900	N	1570	3466	96	17.4	17807
28	900	N	2470	3650	86	21.4	12346
28	900	Y	1056	2455	76.5	16.6	11764
31	900	N	506	1611	70.5	18.8	8898
35	900	N	350	975	67.5	20.6	6186

[d]discontinued prior to fracture at the time indicated

thought that the reduced elongation for the welded specimens may, in part, be a manifestation of the increases thickness of the weld. The lower stress at the weld would be expected to result in less local creep and final extension at failure.

For all test conditions the reduction in area (RA) is generally much less than the elongation. This discrepancy between elongation and RA appears to increase with test temperature and decreasing stress. For example the ratio of elongation to RA is about 4 at 900 °C and 1.9 at 790 °C, similarly the ratio is about 4.5 at 28 MPa and 1.6 at 86 MPa. Such differences suggest that (1) Haynes Alloy 188 sheet is not necking, as confirmed in Fig. 3 and (2) the volume of the gage section is not constant during the creep-rupture test. It is suggested that the gage volume is likely increasing as a result of internal oxidation and/or grain boundary cavitation and oxide intrusion from the external surfaces. Grain boundary opening would be expected to be greater at the lower temperatures, while oxidation phenomena might be more prevalent at the higher temperatures.

The time to 0.5 and 1.0 creep at 790°, 845° and 900 °C as a function of stress are shown in Fig. 4. Estimates based on Tackett's[3] data of the stress required for 0.5 and 1.0 percent creep in 1000 h are shown as "H". The current 0.5 percent creep results are in excellent agreement with Tackett. The 1 percent creep data from this study, Fig. 4(b) agrees with the expectation from Tackett at 845° and 900 °C. At the lowest temperature, the 1 percent creep data appear to indicate that this material is slightly stronger than Tackett's.

Typical creep curves are shown in Fig. 5. Comparing the creep curves at each temperature, one can see that there is little or no period of "steady-state" creep. As the temperature increased, it appears that the shape of the curves above about 0.5 percent tend to change from being concave-down to concave-up. This change might reflect the change

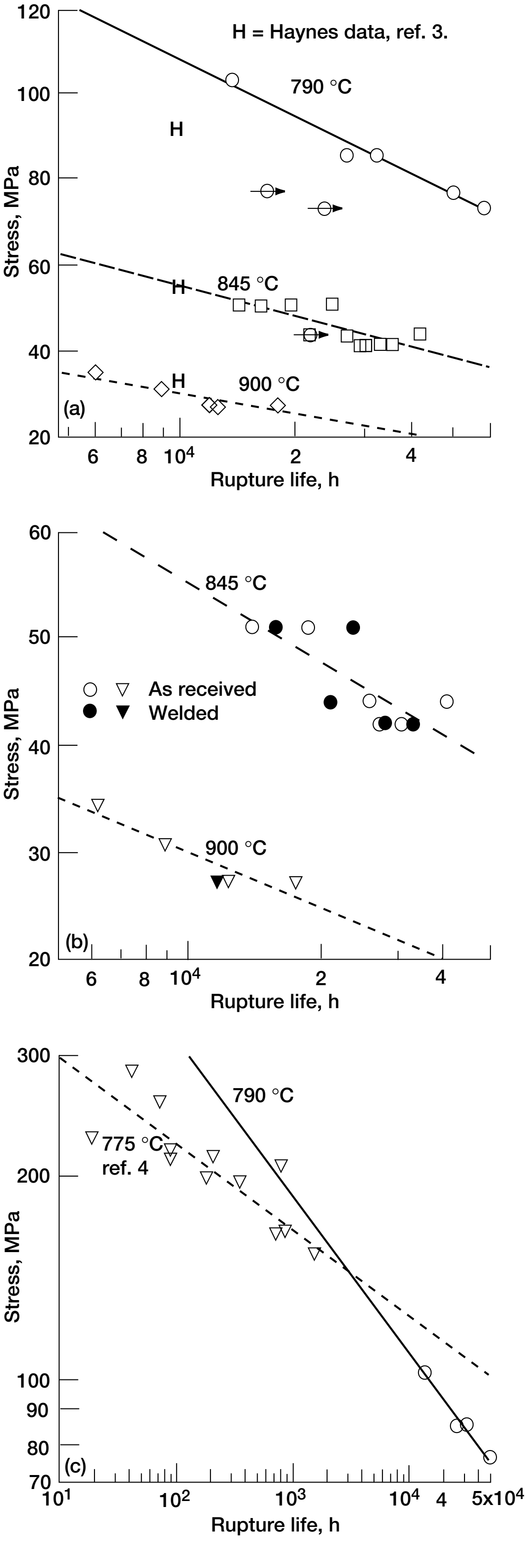

Figure 2.—(a) Stress rupture of Haynes alloy 188. (b) welds had little effect on rupture life. (c) Low temperature rupture data compares well with Whittenberger's.

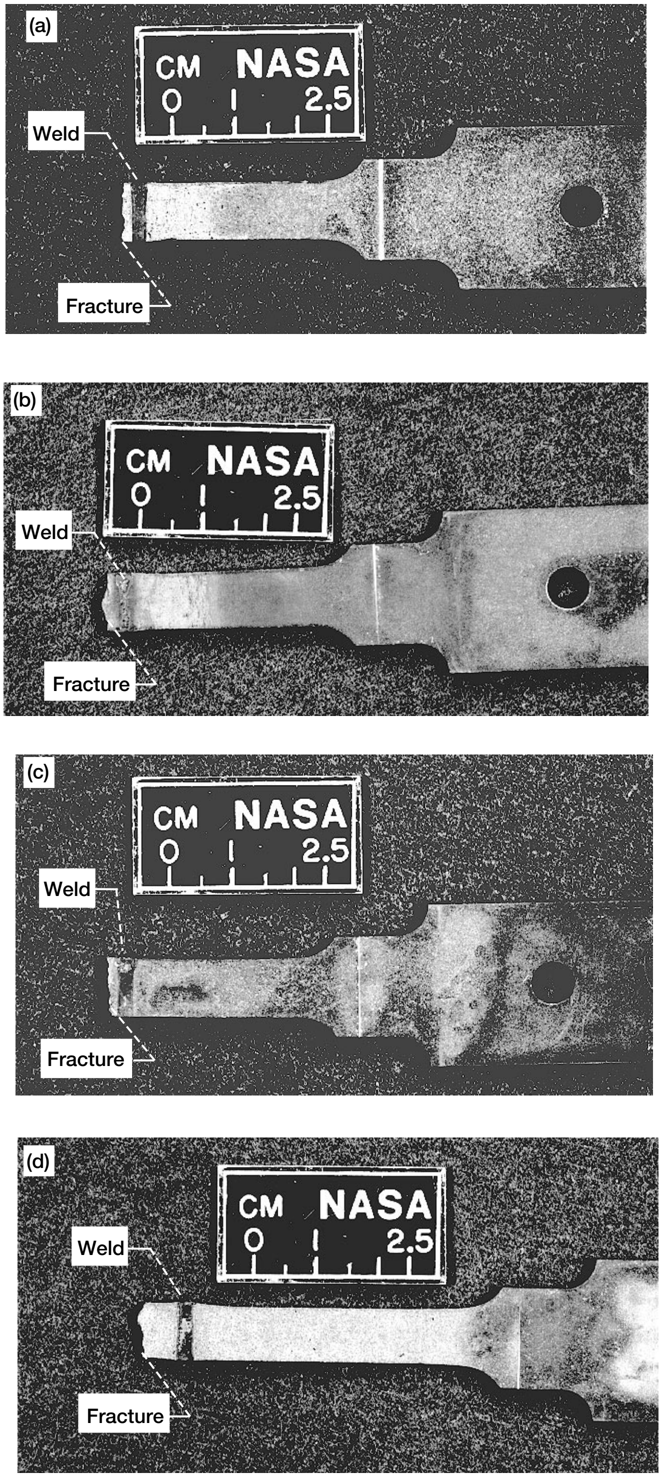

Figure 3.—Welded stress rupture samples failed in the base metal. (a) 845 °C, 42 MPa, 33370 h; (b) 845 °C, 51 MPa, 24111 h; (c) 845 °C, 42 MPa, 28540 h; (d) 900 °C, 28 MPa,11764 h.

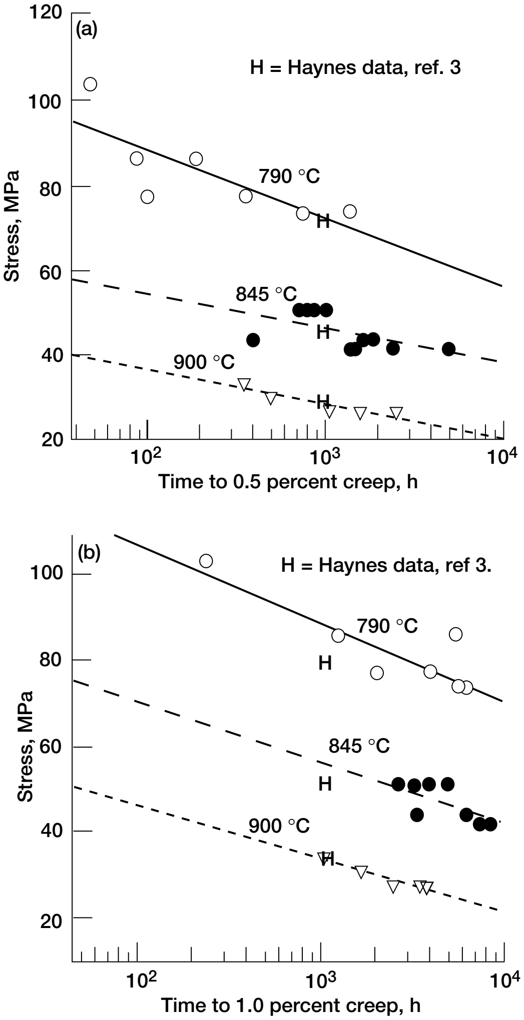

Figure 4.—Creep of Haynes alloy 188. (a) 0.5 percent creep. (b) 1 percent creep.

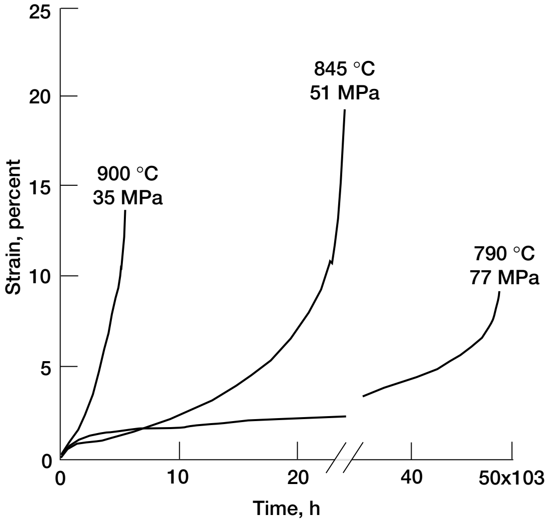

Figure 5.—Typical creep curves.

Table II Summary of Tensile Tests

Condition	Creep temp, ˚C	Creep time, h	Creep strain, %	Tensile temp. ˚C	0.2% yield, MPa	UTS, MPa	Elong., %
as rec'd	845	21150	7	room	466	692	2.5
weld	790	23230	3	room	389	525	0.5
as rec'd	790	16518	0.5	480	390	735	5.5

from continuous work-hardening at the lowest temperature to dynamic recovery overwhelming the effects of work hardening at the highest temperature observed. The very high ductilities observed at 900 °C support the idea that significant recovery is occurring at that temperature.

Tensile Tests

Because other programs at the Lewis Research Center required the use of creep test frames three creep rupture tests were discontinued prior to fracture. These specimens were then tensile tested, Table II. Two were tested at room temperature and one at 480 °C.

The tensile tests results are compared with as-received material and tests performed on the same lot of material after 22,500 h exposure to air at 820 °C[5] in Fig. 6. In Fig. 6(a), it can be seen that the room temperature ultimate tensile strength of the creep tested specimens was reduced 30 to 40 percent compared to either as-received material or that which had been aged without applied stress. The test performed at 480 °C compared well with both as-received and aged material from the earlier work. Figure 6(b), however, shows that the elongation, measured at either test temperature, was severely degraded by the prior creep exposure. The room temperature elongation was reduced to 0.5 and 2.5 percent from an as-received value in excess of 45 percent and an 820 °C aged value of 16 percent. At 480 °C the ductility was only 5.5 percent compared to an as-received value of 29 percent and an aged value of 19 percent.

Metallographic Evaluation

The microstructure of the as-received material shown in Fig. 7(a) consists of a twinned cobalt-base matrix and dispersed particles which are assumed to be M_6C and lanthanides. The microstructures observed in this study are consistent with those reported by Herchenroeder.[7]

The structure after 13441 h at 790 °C and 103 MPa is shown in Figs. 7(b) and (c). The grain boundaries and prior twin boundaries are decorated with precipitates and the intergrannular precipitates are coarsened. Oxide spikes originating at the sheet surface have penetrated to a depth of about 60 µm.

After 22,115 h at 845 °C and 44 MPa the oxide spike penetration is about 100 µm, Fig. 7(d). In addition, there are oxidized pores across the full thickness near the fracture. The presence of oxidized pores is even more pronounced in Fig. 7(e) which shows the structure of a specimen which failed after 6,186 h at 900 °C. It is probable that internal damage is responsible for the loss of tensile ductility observed in the interrupted creep specimens. The general structure after 22,115 h at 845 °C is

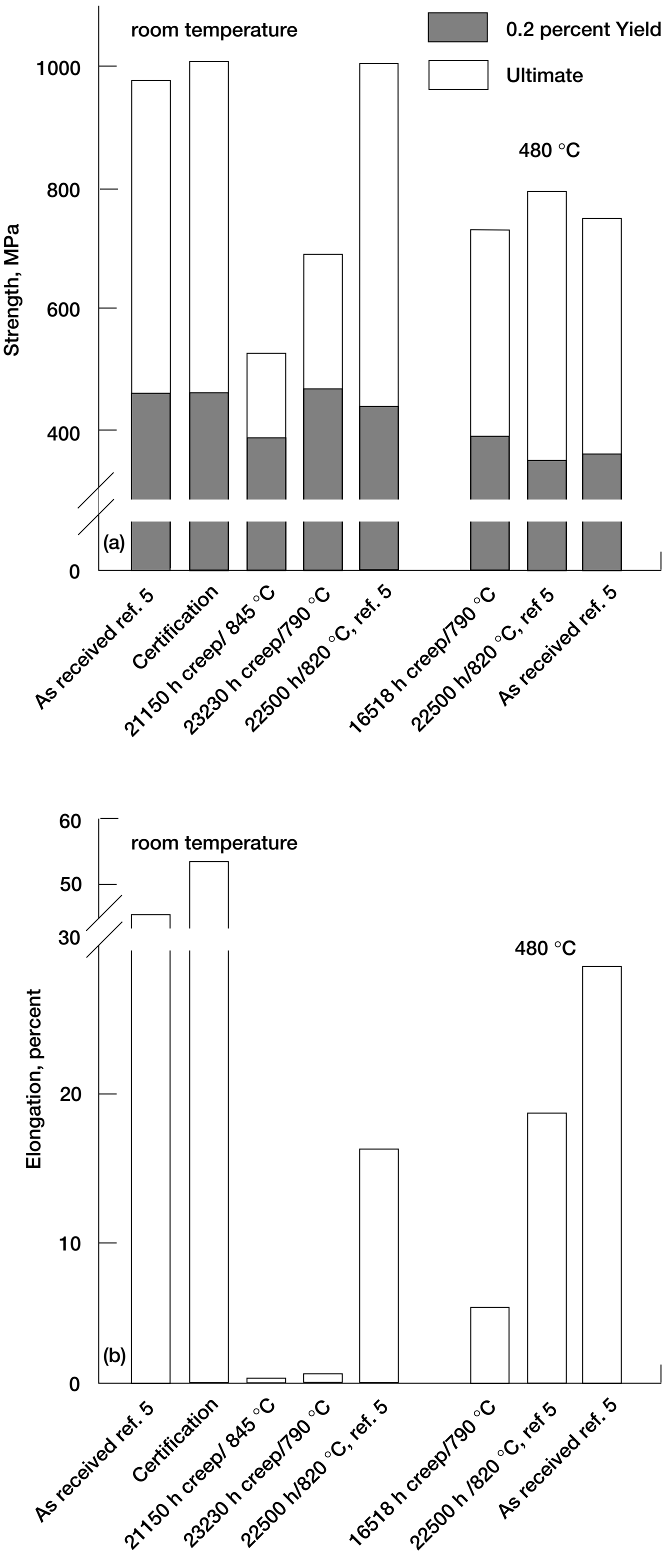

Figure 6.—Effect of prior creep on tensile properties. (a) Strength. (b) Elongation

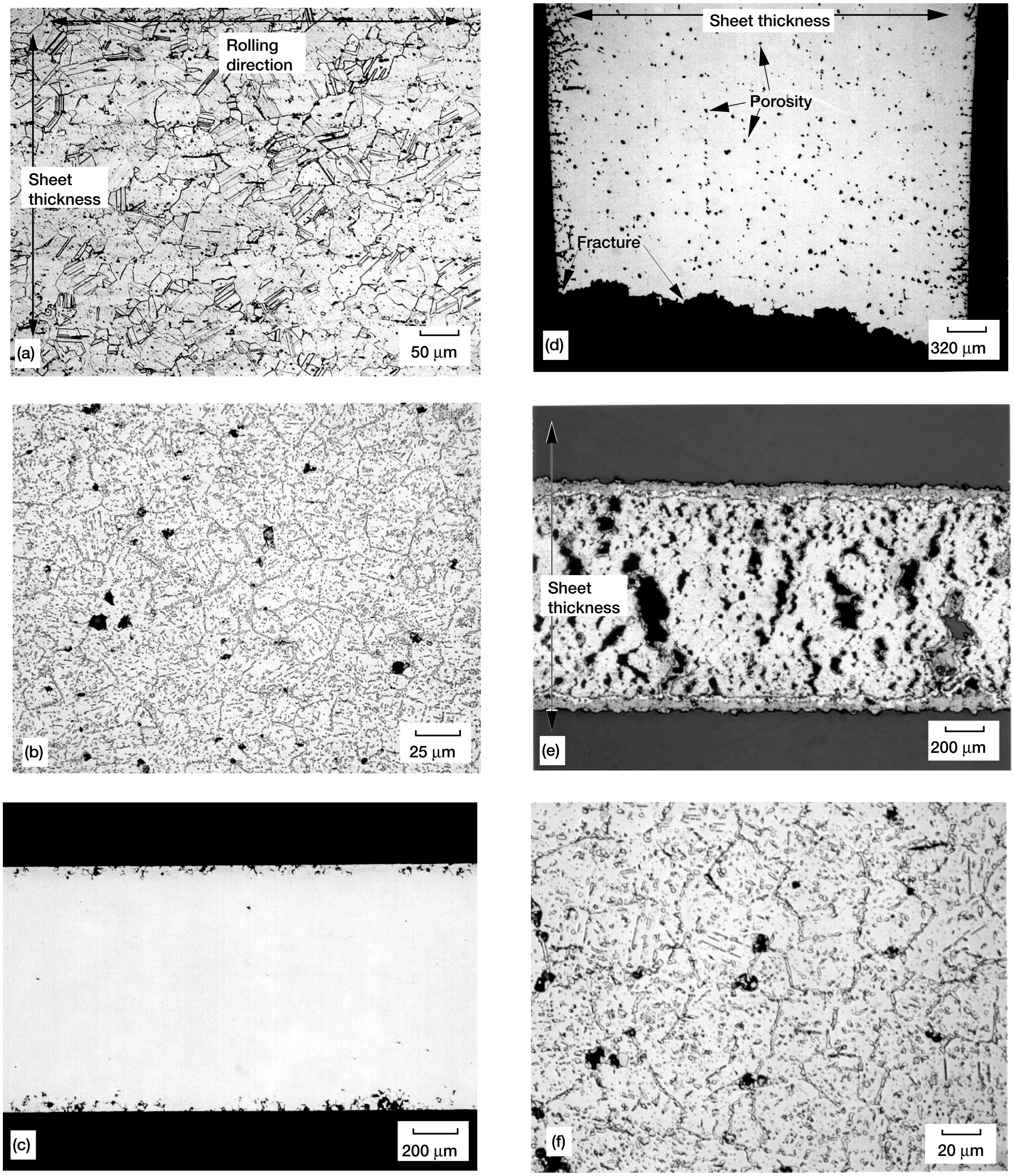

Figure 7.—Selected photomicrographs. (a) As received. (b) Transverse section 13441 h at 790 °C etched. (c) Transverse section 13441 h at 790 °C unetched. (d)Longitudinal section 22115 h, 845 °C unetched. (e) Longitudinal section 6186 h, 900 °C unetched. (f) Longitudinal section 22115 h, 845 °C etched.

shown in Fig. 7(f). It resembles Fig. 7(b), but the precipitates are coarser as a result of the longer exposure at higher temperature.

X-ray diffraction analyses were performed on residues from extractions using electrolytic HCl solution. The major phase identified was a Laves phase. An M_6C carbide could also be identified in specimens tested at both 790° and 845 °C. A very small amount of $M_{23}C_6$ was present in a specimen which failed after 21,150 h at 845 °C.

Selected cross sections were also examined in a scanning electron microscope. Figure 8 is a back-scatter electron image of a specimen which failed after 33,370 h at 845 °C and 421 MPa. The blocky light phase was apparent in specimens tested at all three temperatures and had the following approximate stoichiometry: $(Co_{.27}Ni_{.11}Fe_{.01}Cr_{.28}W_{.33})_{6.9}C$. A similar appearing phase was found in a specimen tested at 790 °C, but it did not appear to contain C. It had the following composition: $Co_{.37}Ni_{.1}Fe_{.01}Cr_{.23}W_{.29}$. It is thought that this phase is probably a Laves phase as one can interpret it as being of the form M_2B, with W being on the B site while all other elements are on A sites. It is noted, however that if one ignores the C content in the M_6C, the composition of that carbide and the Laves phase are similar. Internal Cr rich oxides and carbo-nitrides were identified in specimens tested at 900 °C and in a specimen tested at 845 °C for 33,370 h.

Summary And Conclusions

A study was performed to evaluate the creep-rupture behavior of Haynes Alloy 188 sheet at temperatures from 790° to 900 °C and times in excess of 30,000 h. Comparison of the rupture data to previously published results suggests that the heat of material studied here is equivalent to the Haynes data at 845° and 900 °C and somewhat superior at 790 °C. The time to 0.5 and 1 percent creep strain was comparable to that previously published by Haynes. While the sheet finishing technique had been changed, the slight difference between the lower temperature stress rupture behavior can not be ascribed to that change because of the limited data in this study.

The TIG welded specimens in the present work had virtually the same creep rupture lives as non-welded material. Thus it appears that the engineering creep-rupture behavior of welded Haynes Alloy 188 is the same as non-welded material.

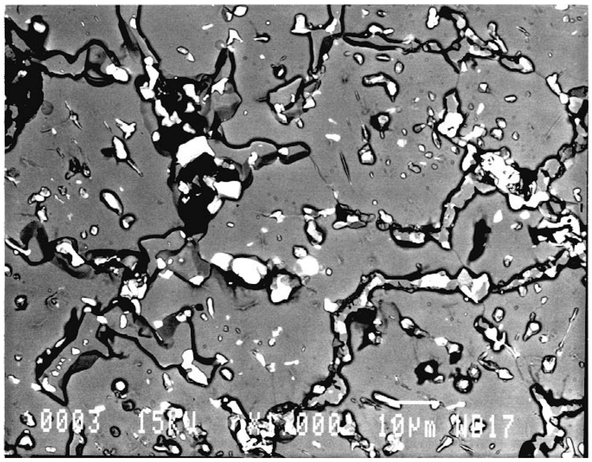

Figure 8.—Backscatter electron image 845 °C 33370 h.

Three creep specimens were removed from test prior to fracture and subsequently tensile tested. Tests at both room temperature and at 480 °C showed extreme loss in ductility. The room temperature tests showing only about 1 percent elongation and the 480 °C test having only about 5 percent. This loss is believed to be associated with internal creep damage across the thickness of the sheet. While it is not likely to be of significance for the proposed Space Station application where the alloy will be exposed either to salt, vacuum or an inert gas, it would be prudent to study this phenomenon in greater detail if a long-life solar dynamic system is to be deployed.

In closing it is appropriate to comment that a 2.0 kW solar dynamic conversion system using many components of the system which was originally developed for Space Station Freedom has been successfully tested in a vacuum tank using a solar simulator at the Lewis Research Center.[8]

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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (*Leave blank*)

2. REPORT DATE
April 1996

3. REPORT TYPE AND DATES COVERED
Technical Memorandum

4. TITLE AND SUBTITLE
Long Time Creep Rupture of Haynes™ Alloy 188

5. FUNDING NUMBERS
WU–547–10–11

6. AUTHOR(S)
Robert L Dreshfield

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

National Aeronautics and Space Administration
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Cleveland, Ohio 44135–3191

8. PERFORMING ORGANIZATION REPORT NUMBER
E–10163

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

National Aeronautics and Space Administration
Washington, D.C. 20546–0001

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
NASA TM–107191
Corrected Copy

11. SUPPLEMENTARY NOTES
Responsible person, Robert L. Dreshfield, organization code 5120, (216) 433–3267.

12a. DISTRIBUTION/AVAILABILITY STATEMENT

Unclassified - Unlimited
Subject Category 26

This publication is available from the NASA Center for AeroSpace Information, (301) 621–0390.

12b. DISTRIBUTION CODE

13. ABSTRACT ***(Maximum 200 words)***

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14. SUBJECT TERMS
Superalloys; Cobalt alloys; Creep; Rupture

15. NUMBER OF PAGES
10

16. PRICE CODE
A03

17. SECURITY CLASSIFICATION OF REPORT
Unclassified

18. SECURITY CLASSIFICATION OF THIS PAGE
Unclassified

19. SECURITY CLASSIFICATION OF ABSTRACT
Unclassified

20. LIMITATION OF ABSTRACT