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HIGH-TEMPERATURE LOW-CYCLE FATIGUE AND TENSILE PROPERTIES OF HASTELLOY X AND ALLOY 617 IN AIR AND HTGR-HELIUM*

J. P. Strizak, C. R. Brinkman, and P. L. Rittenhouse
Metals and Ceramics Division
Oak Ridge National Laboratory
Oak Ridge, Tennessee 37830

ABSTRACT

Results of strain controlled fatigue and tensile tests are presented for two nickel base solution hardened alloys which are reference structural alloys for use in several high temperature gas cooled reactor concepts. These alloys, Hastelloy X Inconel 617, were tested at temperatures ranging from room temperature to 871°C in air and impure helium. Materials were tested in the solution annealed as well as in the pre-aged condition where aging consisted of isothermal exposure at one of several temperatures for periods of up to 20,000 h. Comparisons are also given between the strain controlled fatigue lives of these alloys and several other commonly used alloys all tested at 538°C.

INTRODUCTION

Hastelloy X and Inconel 617, both solid-solution strengthened Ni-base alloys, are currently reference materials for fabrication of a number of high-temperature components of HTGR steam cycle/cogeneration and reformer systems. The first of these alloys, Hastelloy X, has been used successfully for almost three decades in a variety of elevated-temperature applications requiring high strength. Its most extensive use in the HTGR is expected to be as a thermal barrier cover plate material. Industrial experience with the second alloy, Inconel 617, is much more limited but this alloy does have the distinction of possessing very high creep resistance at elevated temperatures. For this reason, it is considered

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as the leading candidate for construction of the intermediate heat exchanger associated with the reformer system.

The HTGR applications anticipated for these alloys require that low-cycle fatigue data be available to satisfy demands relating to engineering design data, codes (e.g., as in Section T-1400 of ASME N-47-17), and licensing. In addition to the basic low-cycle fatigue data, information is needed relative to the effects of service life and environment, particularly as carburization may be expected at elevated temperatures in HTGR primary coolant helum. To satisfy the above, a program of low-cycle fatigue testing was undertaken on Hastelloy X and Alloy 617. The baseline data were determined on solution annealed (unaged) materials. Specimens aged for up to 20,000 h at anticipated service temperatures were then tested for comparison. Both air and HTGR-helium were used as test environments.

MATERIALS CHARACTERIZATION

Materials used in this study came from several commercial sources and are characterized in Table 1.

Hourglass shaped gage section fatigue specimens were fabricated from blanks cut from the plate materials characterized in Table 1. The gage diameter of the resultant specimens was 5.08 mm with a radius to diameter ratio (R/D) of 6. The surface finish of the gage section was 0.20 to 0.28 μm. Tensile test specimens were fabricated with a 6.35-mm-diam and a 31.8-mm gage length. In addition to fabricating specimens in the solution annealed condition, specimens were also fabricated from blanks that had been aged in an argon environment for periods of either 10,000 or 20,000 h at 538, 704, or 871°C. All specimens for fatigue and tensile tests were taken with their major axis parallel to the plate rolling direction.

EXPERIMENTAL

Strain controlled fully reversed fatigue tests were conducted at temperatures ranging from room temperature to 871°C and a cyclic strain rate of $4 \times 10^{-3}s^{-1}$ unless stated otherwise. Desired temperatures were achieved by induction heating. Fatigue tests were conducted in air and in a typical service environment for gas-cooled reactors which is impure helium. The composition of the gas was 300 μatm H_2, 30 μatm CH_4, 20 μatm CO, and 2 μatm H_2O, while the gas pressure in the environmental chamber was 83 kPa gage (1.8 atm). Additional details concerning experimental equipment used in conducting the fatigue tests can be found elsewhere.[1]

Tensile tests were conducted at a 0.004/min. nominal strain rate [0.005 in./min. (0.13 mm/min.) crosshead speed] at temperatures ranging from room temperature to 871°C.

RESULTS AND DISCUSSION

A comparison of the tensile properties for these two alloys is given in Fig. 1. It is apparent for the indicated heats that these materials have similar tensile properties in the solution annealed condition. Hastelloy X showed a characteristic ductility[2] minimum over the temperature range of about 500 to 750°C in both the solution annealed and aged conditions. Thermal aging did not significantly change the ultimate tensile strength of Hastelloy X over the temperature range studied, but there was some indication that aging for periods of about 2,500 h at 700°C increased the yield strength and ductilities. However, continued aging tended to restore these properties to the original solution annealed values. In the case of Inconel 617 there was an indication of a slight increase in tensile strength with aging time particularly at 700 and 871°C. Yield strengths increased at 538 and 700°C with increasing aging times while ductilities dropped slightly.

Figure 2 contains a summary plot of all known United States load and strain controlled fully reversed fatigue data generated in air and available at room temperature for Hastelloy X.[1,3,4] These data, along with other data to be generated at 427°C, will be combined and serve as the basis for fatigue curves to be submitted to the American Society For Mechanical Engineers (ASME) Code formulating bodies for consideration in fatigue design in Sections III and VIII of the Code. In curve fitting the data, load controlled data were omitted from the analysis if the specimen did not fail or if failure occurred at cycle lives less than 10^6 cycles. Hastelloy X is a cyclic hardening material and it was felt that load controlled data with cycle lives less than about 10^6 cycles were influenced by a variable range in plasticity and, therefore, were not equivalent to the strain controlled data. These data are quite similar to those for the stainless steels.[5]

Figure 3 contains additional strain controlled data for Hastelloy X generated at several temperatures in air to 871°C. Data shown were generated at ORNL[1] and by Jaske.[6] A significant decrease in continuous cycle fatigue life is apparent between room temperature and 538°C. Hence additional data will be generated in air at 427°C before submitting the data given in Fig. 2 to the ASME Code.

Figures 4 and 5 compare data generated from Hastelloy X specimens in the solution annealed or solution annealed plus aged condition in which the aging and test temperature were identical. Data plotted in Fig. 4 were generated at 538°C in either an air or impure helium environment. Little or no effect of the helium environment is seen on resultant fatigue life in comparison to data obtained in air, but thermal aging prior to testing can reduce fatigue life depending upon the prior exposure time. Similarly, Fig. 5 shows that a thermal aging treatment for 10,000 h decreases resultant low cycle life when the material aging and test temperature are 871°C, but that cycle life is restored when the thermal aging time is extended to 20,000 h. These changes are probably due to subtle changes in the microstructue and resultant changes in ductility. Most of the data given in Figs. 3–5 were fit as the sum of two simple power law terms for the elastic and plastic components of the total strain range. The results of this analysis are given in Table 2 for Hastelloy X.

Results of similar tests conducted on Inconel 617 are plotted in Figs. 6–8 with power law fit constants given in Table 3 for data generated at 538, 704, and 871°C. With respect to the effects of thermal aging, the results obtained to date indicate a mixed response. At 538°C there appears to be a clear trend that long term thermal aging results in improved cycle life with increasing time. Aging for 10,000 h prior to testing at 704°C appears to reduce fatigue life somewhat at this temperature as is shown in Fig. 7, but aging for 20,000 h at this temperature improved fatigue life slightly. Similar trends were noted in the data generated at 871°C as shown in Fig. 8. These changes were attributed to microstructural changes noted in post-test examination of the specimens.

Comparing the data generated in impure helium with those generated in air, Figs. 6-7, it is apparent that the helium environment was in no case detrimental to fatigue life and, in fact, was usually beneficial.

Finally, Fig. 9 gives a comparison plot of these two alloys in the solution annealed condition versus other commonly used structural alloys showing the strain controlled fatigue life at 538°C. Differences become particularly apparent in the high cycle region. It is also noted that Hastelloy X has a higher fatigue resistance than Inconel 617 when both are compared in the solution annealed condition. Fig. 10 compares cyclic stress strain curves for these alloys based on $N_f/2$ values of stress. Little or no difference is apparent between these two alloys and no effect of thermal aging was noted.

CONCLUSIONS

A comparison was made of available strain controlled fatigue data of Hastelloy X and Inconel 617 from room temperature to 871°C. Results included continuous cycling data obtained in air and an impure helium environment. Data were presented that had been generated on these alloys in the solution annealed as well as in the solution annealed and aged condition. Pre-aging of the alloys occurred for times up to 20,000 h. We concluded the following:

1. Thermal aging did not significantly alter the ultimate tensile strength of Hastelloy X; however, there were some indications of changes in the yield strength and ductility properties depending upon aging time and temperature. In the case of Inconel 617, thermal aging increased the

tensile and yield strengths somewhwat while ductilities decreased slightly again depending upon aging conditions.

2. Low and high cycle fatigue properties of Hastelloy X generated at room temperature are similar to those of the austenitic stainless steels. However, as the temperature is increased differences become apparent, particularly out at the high cycle end of the curves with Hastelloy X showing the superior resistance to isothermal fatigue.

3. Prior thermal aging of Hastelloy X at either 538 or 871°C was seen to reduce fatigue life slightly depending upon the aging time. Testing of this alloy in an impure helium environment resulted in no significant change in low cycle fatigue resistance.

4. The influence of prior thermal aging on the elevated temperature low cycle fatigue behavior of Inconel 617 was found to be dependent upon time and temperaure and both small increases and decreases were found in subsequent fatigue life. An impure helium environment was generally beneficial or resulted in little or no change in fatigue resistance of this alloy.

5. Hastelloy X shows low cycle fatigue properties superior to those of Inconel 617 when tested at elevated temperatures (538°C) in an air environment.

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3. D. A. Jablonski, "Fatigue Behavior of HASTELLOY - X at Elevated Temperature in Air Vacuum and Oxygen Environments," PhD thesis, Department of Material Science and Engineering, MIT, February 1978.
4. Cabot data files; Cabot Corporation, Kokomo, Indiana, Courtesy of A. Aizaz.

5. B. F. Langer, "Design of Pressure Vessels for Low-Cycle Fatigue," Trans. ASME, Sept. 1962, pp. 389–402.

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Table 1. Alloy Characterization

Material	Heat	Source	Product Form	Heat Treatment	Grain Size (μm^2)
Inconel 617	XX01A3U5[a]	INCO[b]	12.7-mm (1/2-in.) plate	Solution annealed at 1177°C followed by a rapid cool	31.0 (ASTM 2)
Hastelloy X	2600-3-4936[c]	Cabot			7.8 (ASTM 4)

[a] 57.35 Ni, 20.30 Cr, 11.72 Co, 8.58 Mo, 1.01 Fe, 0.76 Al, 0.16 Si, 0.07 C, 0.05 Mn, 0.004 S (wt %).

[b] International Nickel Company.

[c] 21.82 Cr, 1.68 Co, 9.42 Mo, 19.09 Fe, 0.44 Si, 0.07 C, 0.58 Mn, <0.005 S, 0.63 W, bal Ni (wt %).

Table 2. Values of Constants and Exponents Describing the Best Fit Fatigue Curves[a] for Hastelloy X (Heat 2600-3-4936)

Temperature (°C)	$\Delta\varepsilon_t(\%) = AN_f^{-a} + BN_f^{-b}$			
	A	a	B	b
	Solution Annealed Material			
22	56.75	0.489	1.607	0.126
538	201.3	0.753	1.288	0.093
649	87.70	0.730	1.191	0.089
704	50.35	0.623	0.736	0.0631
871	67.2	0.657	0.537	0.065
	Material Aged 10,000 h[b]			
538	56.3	0.642	1.288	0.093
871	60.8	0.682	0.929	0.125
	Material Aged 20,000 h[b]			
538	192.3	0.761	1.288	0.093
871	53.1	0.627	0.929	0.125

[a] Strain controlled fatigue testing at a strain rate of 4×10^{-3}/s.

[b] Aged in argon at the respective test temperature.

Table 3. Values of Constants and Exponents Describing the Best Fit Fatigue Curves[a] for Inconel 617 (Heat XXX01A3U5)

Temperature (°C)	$\Delta\varepsilon_t(\%) = AN_f^{-a} + BN_f^{-b}$			
	A	a	B	b
	Solution Annealed Material			
538	67.9	0.687	1.530	0.127
704	70.8	0.738	1.379	0.121
871	128.0	0.843	0.953	0.138
	Material Aged 10,000 h[b]			
538	38.17	0.606	1.530	0.127
704	70.3	0.774	1.379	0.121
871	218.1	0.983	0.953	0.138
	Material Aged 20,000 h[b]			
538	106.9	0.693	1.530	0.127
704	72.7	0.792	1.379	0.121
871	245.9	0.941	0.953	0.138

[a] Strain controlled fatigue testing at a strain rate of 4×10^{-3}/s.

[b] Aged in argon at the respective test temperature.

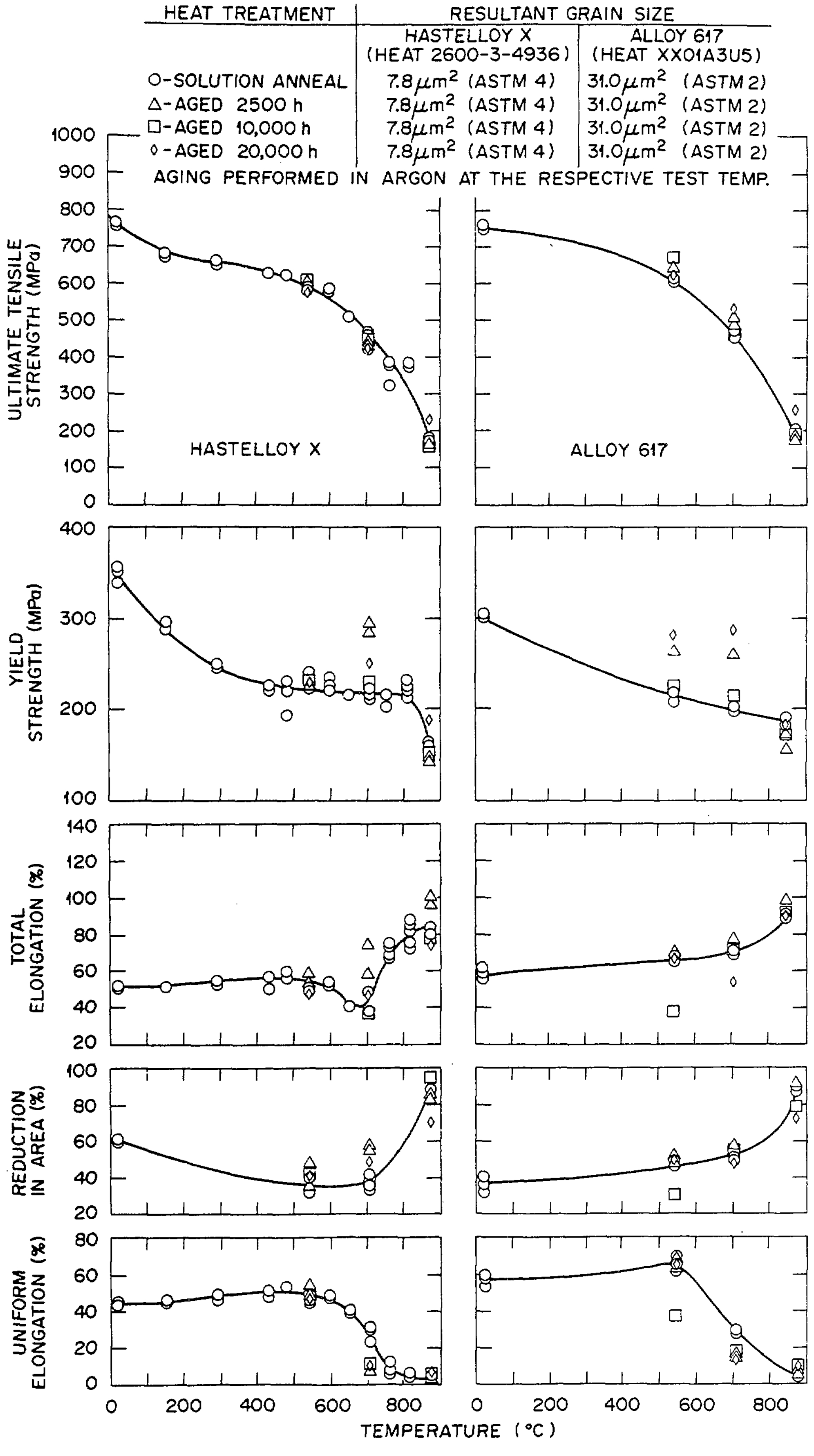

Fig. 1. Comparison of the Tensile Properties of Hastelloy X and Inconel 617 in both the Solution Annealed and Aged Conditions.

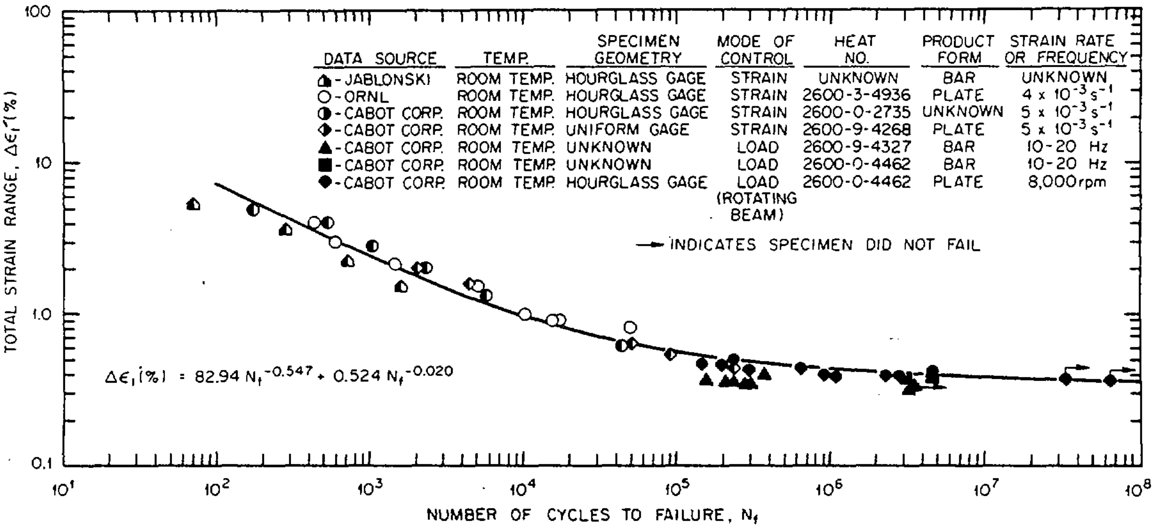

Fig. 2. Comparison of the Data Obtained from Several Heats, Product Forms, and Test Techniques at Room Temperature for Hastelloy X. Note that only load control data from tests that failed in excess of 1×10^6 cycles were used in curve fitting.

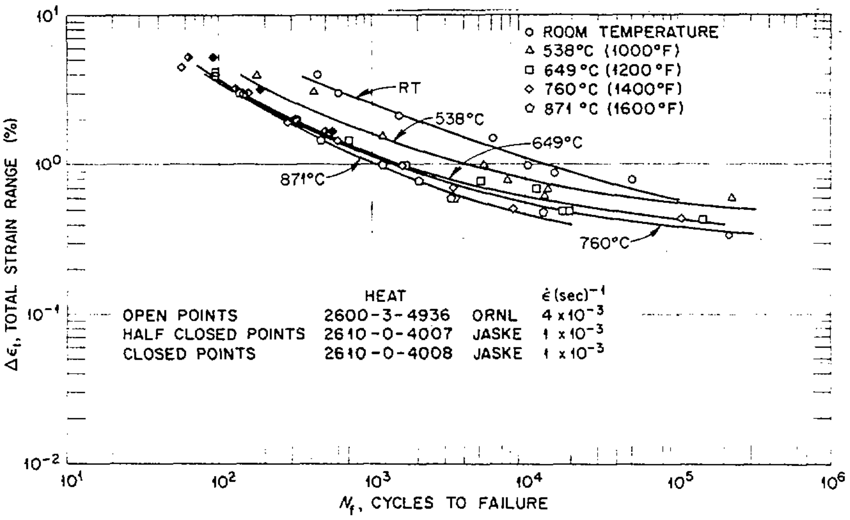

Fig. 3. Total Strain Range vs Cycles to Failure for Hastelloy X Tested in Air.

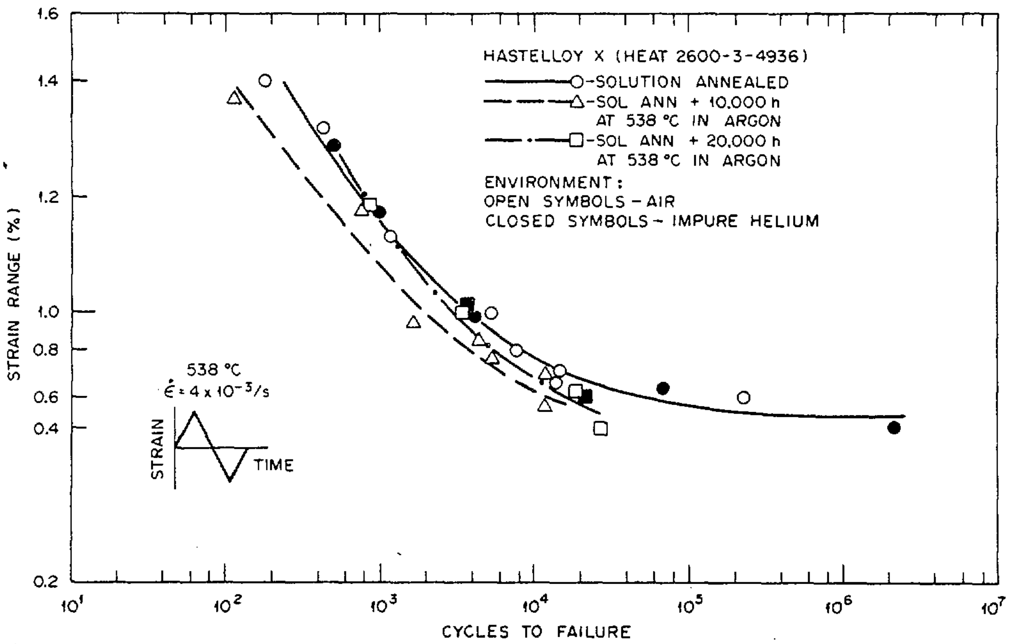

Fig. 4. Comparison of Strain Controlled Fatigue Data Generated at 538°C in Air and Impure Helium For Hastelloy X in Several Conditions.

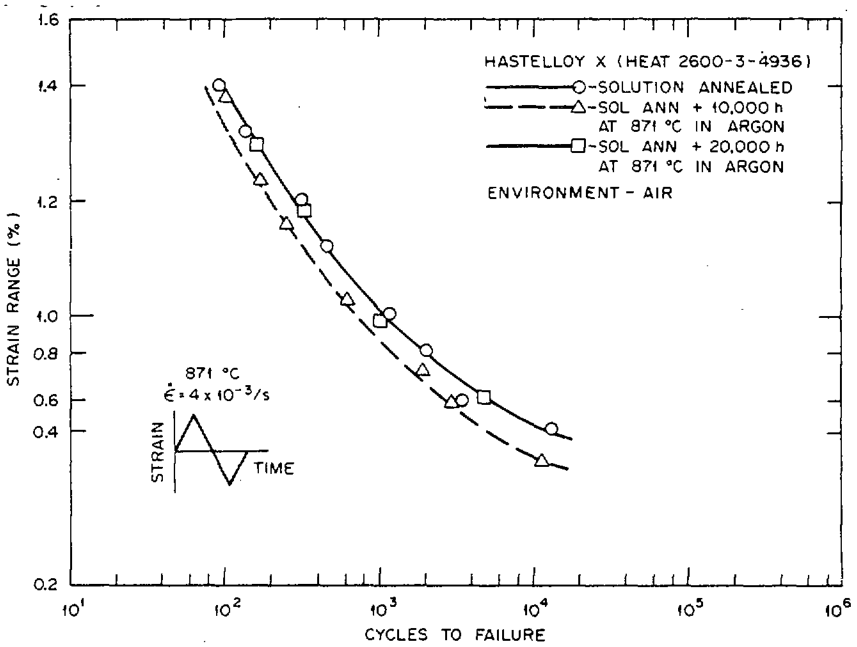

Fig. 5. Comparison of Strain Controlled Fatigue Data Generated at 871°C in Air For Hastelloy X in Several Conditions.

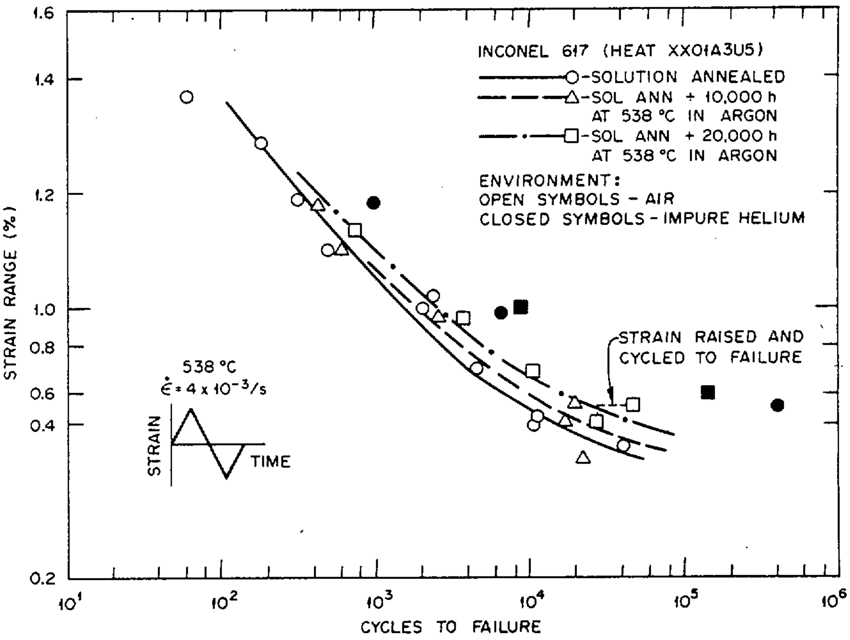

Fig. 6. A Comparison of the Low Cycle Fatigue Behavior of Inconel 617 Tested In Air and Impure Helium at 538°C.

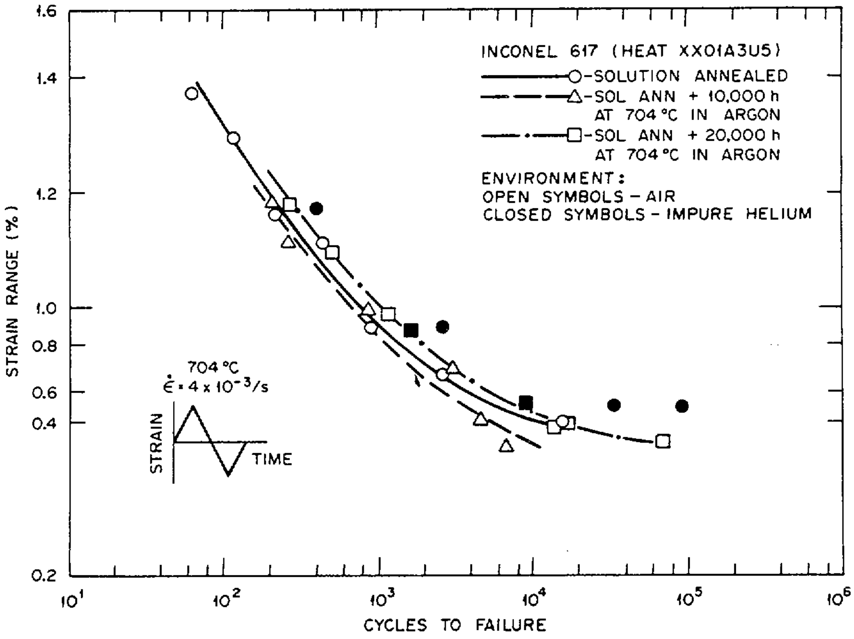

Fig. 7. A Comparison of the Low Cycle Fatigue Behavior of Inconel 617 Tested In Air and Impure Helium at 704°C.

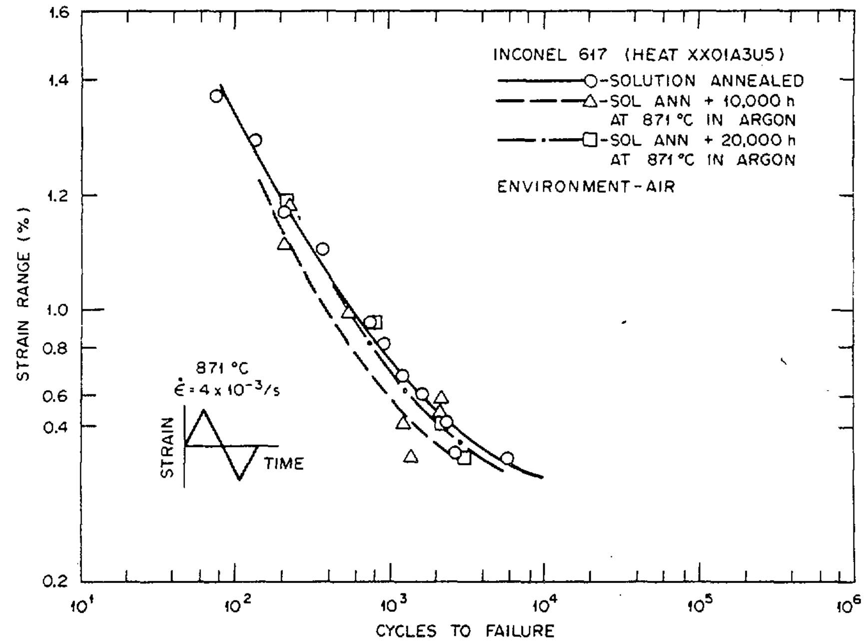

Fig. 8. A Comparison of the Low Cycle Fatigue Behavior of Inconel 617 Tested in Air at 871°C.

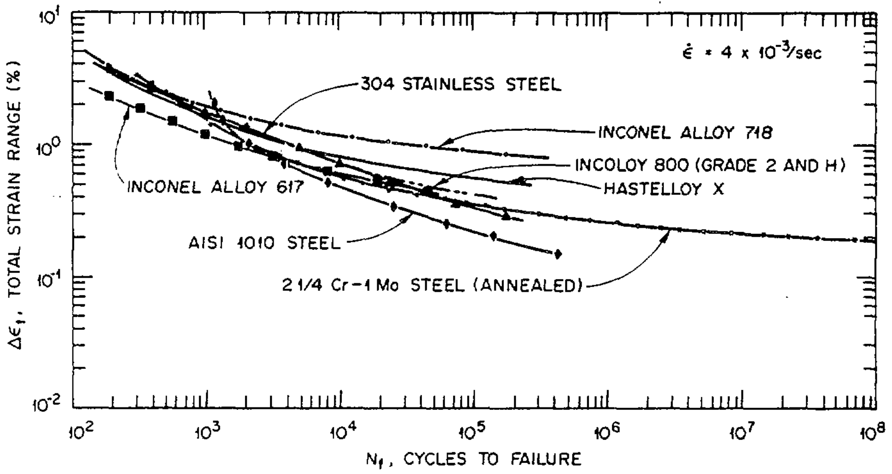

Fig. 9. Comparison of the Fatigue Behavior of Several Materials at 538°C. Lines represent best-fit values of actual data. Data for 304 stainless steel include tests conducted at 538°C and 566°C.

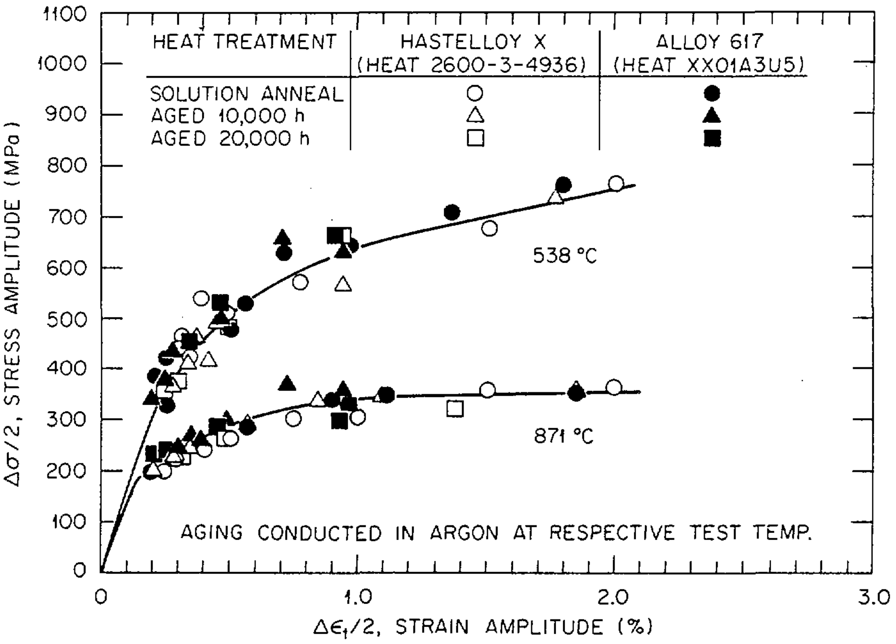

Fig. 10. Cyclic Stress-Strain Curves for Hastelloy X and Inconel 617.