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FATIGUE OF AUSTENITIC STAINLESS STEELS IN THE LOW AND INTERMEDIATE CYCLE RANGE

R. W. Swindeman

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METALS AND CERAMICS DIVISION

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R. W. Swindeman

January, 1966

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ABSTRACT

The data available in the literature on the fatigue characteristics of typical austenitic stainless steels at from 10 to 10^6 cycles and from room temperature to 925°C have been organized and summarized to provide a good basis for the design of high temperature equipment. Comparison of the test data with curves defined by the ASME Boiler and Pressure Vessel Code indicates that failures do not occur until the stress level is 150% to 200% of the ASME Code value for any given set of conditions, the margin varying with the operating temperature and the number of cycles.

FATIGUE OF AUSTENITIC STAINLESS STEELS IN THE LOW AND INTERMEDIATE CYCLE RANGE

R. W. Swindeman

INTRODUCTION

This report presents an accumulation of data concerning the fatigue of austenitic stainless steels in the low and intermediate cycle range (10 to 10^6). There is a growing interest in this particular subject inasmuch as a significant percentage of the failures which occur in high-temperature equipment utilizing stainless steels result from the presence of cyclic stresses. More often than not there are other factors such as material defects, corrosion, geometric discontinuities, etc., which amplify the effect but before we can hope to understand what allowances should be made for such factors we must gain some idea of the basic resistance of these materials to cyclic stresses at elevated temperatures.

Significant progress has been made in this area in recent years. The work of Coffin[1] has shown that the low and intermediate fatigue lives of ductile metals are controlled by the plastic strain range. This information has been incorporated into Section III of the ASME Boiler and Pressure Vessel Code which establishes several new rules for designing against fatigue. The section permits an elastic stress analysis of the component in question and presents conservative design limits, generous enough to permit economical design to metal temperatures not exceeding 427°C for 18-8 stainless steels. A subsequent code case (N 1331-1) extends the analytical technique and provides additional design data to temperatures not exceeding 649°C.

One might ask the reason for accumulating fatigue data on stainless steels if the problem has already been resolved. The answer, of course, is that experimental verification of these design curves is still required.

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[1]J. F. Tavernelli and L. F. Coffin, Jr., A Compilation and Interpretation of Cyclic Strain Fatigue Tests, Trans. Am. Soc. Metals, 51, 438 (1959).

The Atomic Energy Commission is sponsoring a comprehensive program on reactor pipe ruptures[2] which has this as one of the objectives. In the meantime, there seem to be a few areas of concern which should be brought to the attention of the designer.

In addition to this, stainless steels are code approved for use up to 815°C. It would be difficult to eliminate fatigue stresses in mechanisms operating in the temperature range from 650 to 815°C, and it is quite useful to have fatigue data in this area for evaluating the reliability of such structures.

The philosophy of Section III is based on the fact that ductile metals are capable of absorbing a considerable number of plastic strain cycles without failure. If the primary and secondary stress intensity is such that shakedown will occur, that is, if the stress adjustment after plastic yielding will reduce subsequent stresses to the elastic range, fatigue failure is not likely to occur. This is because the limiting elastic stress intensity for stainless steel is below the endurance limit. If shakedown does not occur, a fatigue analysis is acceptable if based on the design curves provided. Designing for fatigue failure is allowed only if the stress in question is a peak local stress; that is, a stress which will not produce distortion in the vessel. Such stresses result from concentration points (notches) or thermal strains.

It is this peak local stress which, in the past, has produced many of the tube and shell fatigue failures in high-temperature systems, and it is to limit their magnitude or number that Section III provides fatigue design curves. Langer[3] describes how these curves were derived. They are based on the following argument. Coffin[1] has found a definite relationship between the plastic strain range, ϵ_p, in a strain-controlled fatigue test and the number of cycles to failure, N_f. This equation:

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[2]H. H. Klepfer, Experimental and Analytical Program Recommendations, Reactor Pipe Rupture Study, GEAP-4474 (January 1965).

[3]B. F. Langer, Design of Pressure Vessels for Low Cycle Fatigue, J. Basic Eng., 84, 389 (September 1962).

$$N_f^{\alpha} \epsilon_p = C \qquad (1)$$

has two constants, α and C, which may be readily evaluated. The constant α is near 1/2 for ductile metals and the constant C is equal to or greater than one half of the true fracture strain, ϵ_f, calculated from the reduction in area corresponding to a standard tensile test. Assuming this to be true, we may generate a total strain fatigue curve (ϵ_T vs N) by adding the elastic component of strain, ϵ_e, to the plastic ϵ_p. This curve, in turn, may be converted into a fictitious stress fatigue curve in terms of stress amplitude, S, by multiplying total strain values by one half the modulus of elasticity. Thus, Langer obtains:

$$S = \frac{E}{4\sqrt{N}} \ln \frac{100}{100 - RA} + \Delta S \qquad (2)$$

where RA is the reduction in area (per cent) and ΔS is the elastic stress given by $E\,\epsilon_e/2$. A conservative estimate for ΔS is the stress endurance limit.

Langer applies a factor of safety of half the stress axis or 1/20 on the cycle axis, whichever is more conservative, to generate the final design curve. The value of the stress amplitude is directly comparable to half the stress intensity calculated by the designer who performs an elastic stress analysis on the component in question.

Coffin[4] shows that Eq. (2) represents a conservative estimate of the true behavior of ductile metals at low temperatures. Manson[5] has obtained data in much the same way and shows that this is not always so. In either case, experimental data are well above the allowed design curve at room temperature.

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[4] J. F. Tavernelli and L. F. Coffin, Jr. Experimental Support for a Generalized Equation Predicting Low Cycle Fatigue, J. Basic Engr., 84, 533, (December 1962).

[5] S. S. Manson and M. N. Hirschberg, Fatigue Behavior in Strain-Cycling in the Low and Intermediate Cycle Range, Fatigue – An Interdisciplinary Approach, p. 133, Syracuse University Press, Syracuse, N. Y., 1964.

Since peak stresses are often associated with thermal strains, one would expect to see a demonstration that the design curves are conservative at temperatures higher than 20°C. Such information is not available in the open literature and consequently is shown in this report. Also included is a discussion which evaluates a few of the many variables which have an influence on high-temperature fatigue behavior.

Rather than to modify the fatigue data to conform to a fictitious stress, S, as was done by Coffin, the design stress curves in Section III and Code Case 1331-1 have been converted to total strain by multiplying stress values by 2/E. Values for E are given in Appendix A. The reader should remember that the safety factors are still included.

Pertinent details regarding the experimental conditions associated with the fatigue data reported in Figs. 1 through 9 are given in Appendix B. Basically, three types of test data are included: isothermal strain-fatigue, isothermal stress-fatigue, and restrained thermal cycling. Isothermal strain-fatigue data are generally the most reliable for evaluating strain-fatigue properties, since strain is the controlled variable. Isothermal stress-fatigue data can be reliable if the strain values are monitored and mean strains not permitted. Restrained thermal-cycling, although it most closely approaches actual design conditions, is often regarded as unreliable because of problems in calculating the unit strains. Where only plastic strains have been reported, reasonable estimates of the elastic strains have been made based on the material modulus and estimated yield strengths. Where only stresses have been reported, these have been converted to strain by dividing by the modulus. In all cases, these were bending tests.

PRESENTATION OF DATA

Figure 1 presents data for four different steels at room temperature. Despite the different compositions, heat treatments, and testing techniques, the alloys show very similar behavior. The only exception is type 310 stainless steel which shows a low endurance beyond 10^5 cycles. The design curve appears conservative over the whole range.

ORNL DWG. 65-13443

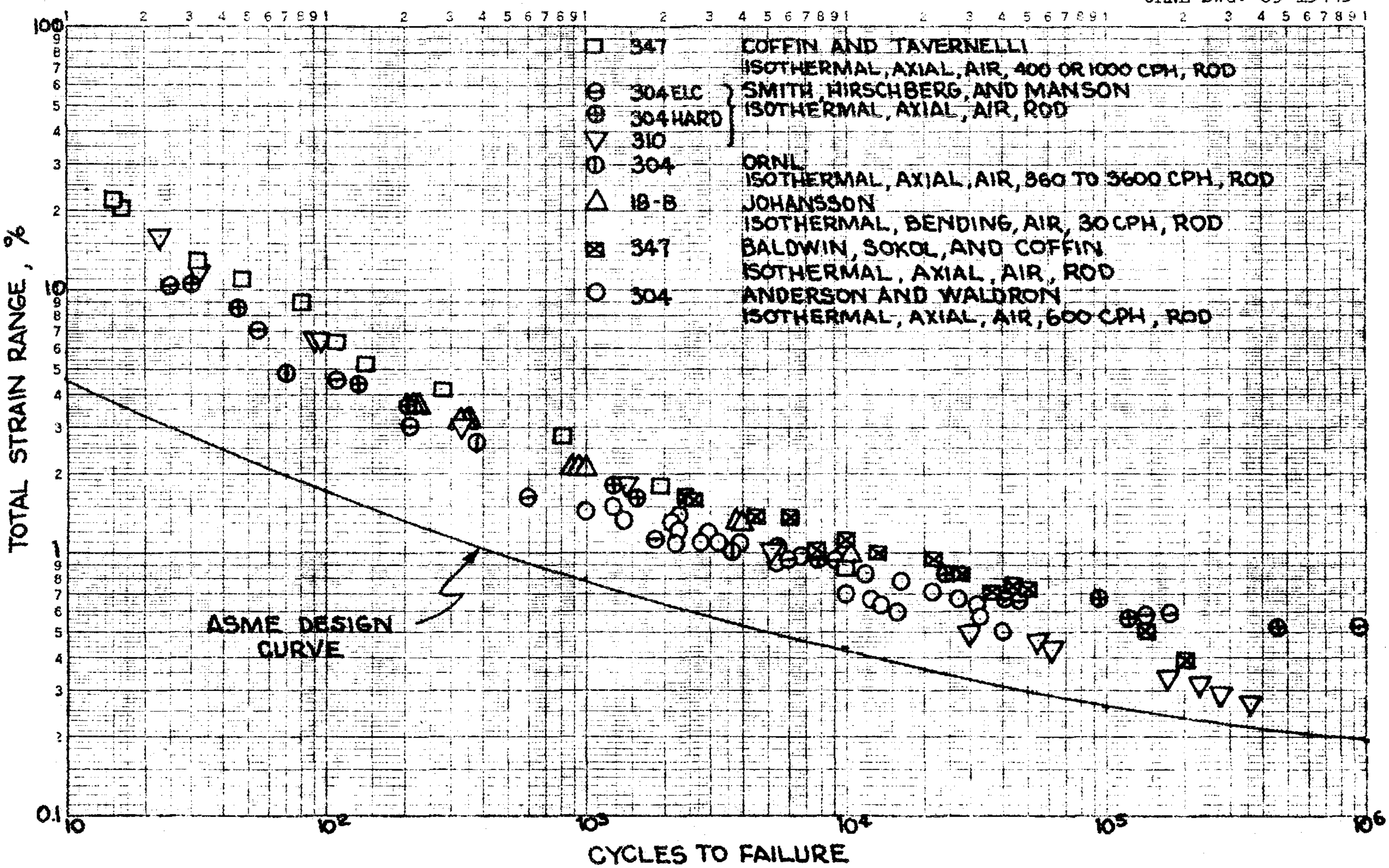

Fig. 1. Fatigue of Stainless Steels at Room Temperature.

Very few data are available in the temperature range from 20 to 450°C; hence all such data have been plotted on the same graph, shown in Fig. 2. The bending data of Johansson[6] on 18 Cr-8 Ni and the axial tests of Baldwin[7] on type 347 stainless steel show the best fatigue resistance. The isothermal data of Horton[8] on type 304L stainless steel thin wall tubing indicate poor performance. Likewise, the thermal fatigue data of Coffin[9] on thin wall type 347 stainless steel tubing and that of Mozharoskii[10] on 1K18N9T (type 321 stainless steel) tubing show poor performance. These data fall close to the design curve in the cycle range between 10^4 and 10^5.

The allowed strain ranges of the ASME design curves rapidly drop between 450 and 550°C and remain conservative in regard to most of the experimental data. Figure 3, which shows data around 500°C, indicates that this is so. The exceptions are the high-strain isothermal data of Horton, the thermal fatigue data of Mozharoskii at low strain levels, and the isothermal data of Walker[11] on type 316 stainless steel plus columbium. Walker's data are interesting because they were obtained on the same machine as Baldwin's data (type 347 stainless steel), also shown in Fig. 3. The only difference is that Walker employed a 12-hr hold time on the tension side of the cycle.

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[6]A. Johannson, Fatigue of Steels at Constant Strain Amplitude and Elevated Temperature, Colloquium on Fatigue, Proceeding, Springe-Verlag, Berlin, p. 112 (1956).

[7]E. E. Baldwin, G. J. Sokol, and L. F. Coffin, Jr., Cyclic Strain Fatigue Studies on AISI type 347 Stainless Steel, Proc. Am.. Soc. Testing Mat., 57, 567 (1957).

[8]K. E. Horton and J. M. Hollander, Investigation of Thermal-Stress-Fatigue Behavior of Stainless Steels, ATL-A-144 (October 31, 1964).

[9]L. F. Coffin, Jr., A Study of the Effects of Cyclic Thermal Stresses on a Ductile Metal, Trans. Am. Soc. Mech. Eng., 76, 931 (August 1954).

[10]N. S. Mozharvskii, On the Problem of Thermal Fatigue of Alloys with the Boundary Conditions Taken into Account, Zavodskaya Laboratoriya, 29, 743 (June 1963).

[11]C. D. Walker, Strain Fatigue Properties of Some Steels at 510°C with a Hold in the Tension Part of the Cycle, Joint Int. Conf. on Creep, Inst. Mech. Eng., London, p. 24 (1963).

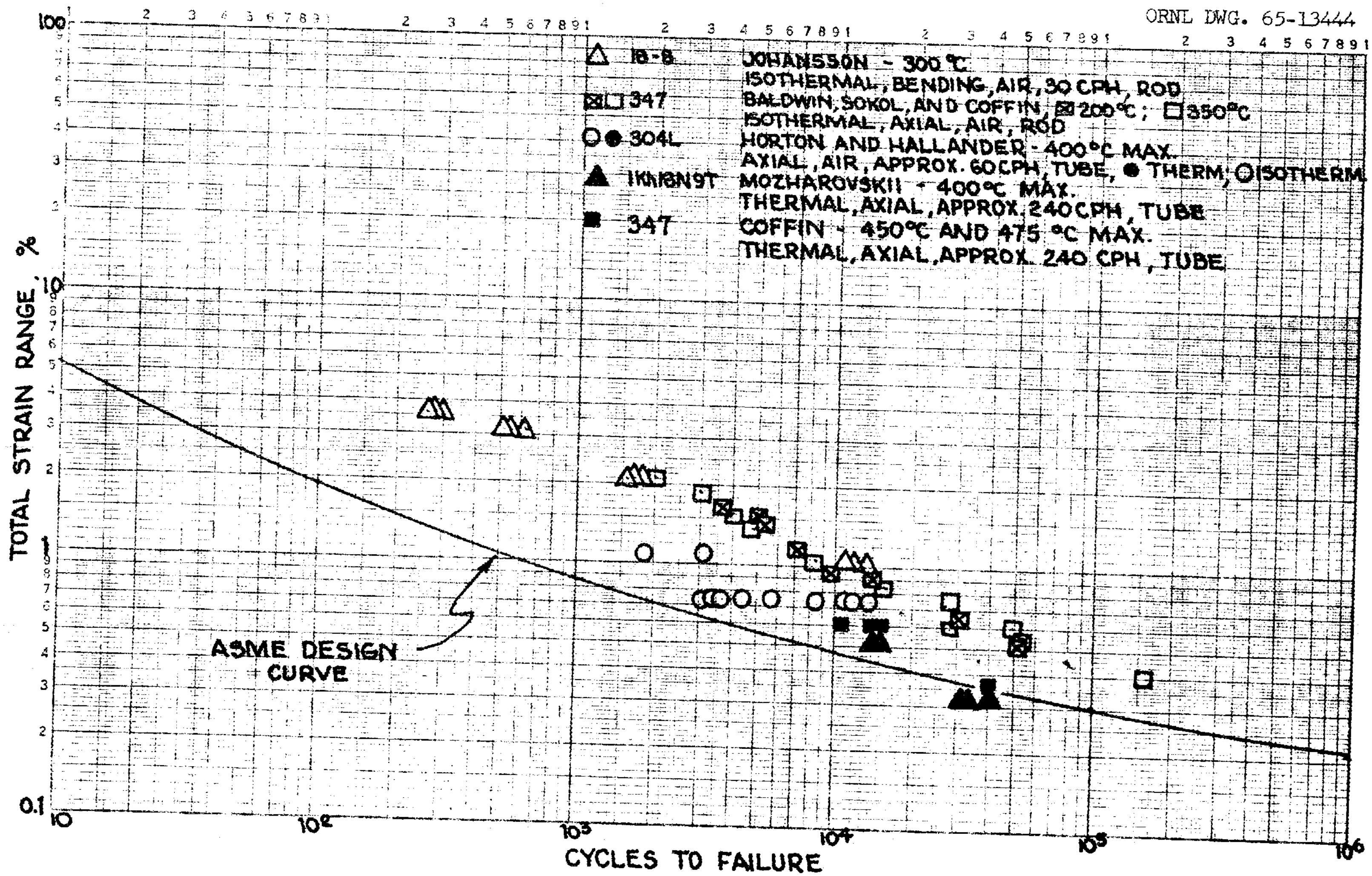

Fig. 2. Fatigue of Stainless Steels Between 20 and 450°C.

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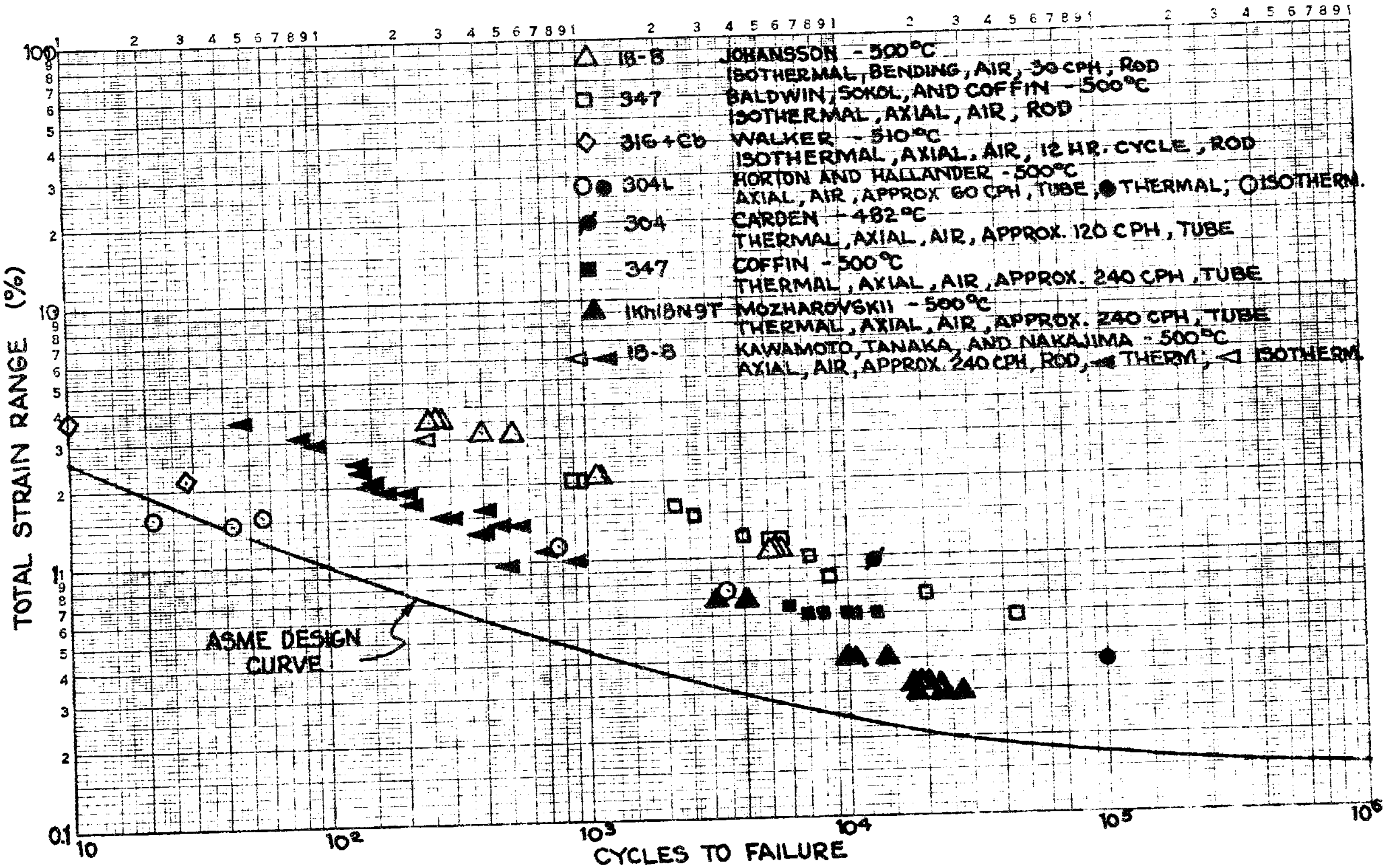

Fig. 3. Fatigue of Stainless Steels Around 500°C.

At 550°C, as shown in Fig. 4, most of the data are well above the design curve. This is also true at 600°C, as indicated in Fig. 5. In both cases, however, some of the points approach the design curves, especially for Mozharvskii"s data.

Data around 650°C are shown in Fig. 6. This is the highest temperature covered by Code Case 1331-1. Available data plot well above the curve with the exception of one test performed by Reynolds[12] on type 304 stainless steel tubing in steam. This test point falls rather close to the design curve.

Fatigue data around 700°C are shown in Fig. 7. The most significant set of data included in this graph is that for the behavior of 1 Kh18N9T (type 321 stainless steel) reported by Balandin.[13] He shows a marked frequency effect in thermal cycling thin wall tubes as the hold time is varied from 1/4 min. to 10 hr. At a strain range of 0.4%, the cycles to failure diminish with increased hold time from around 1200 to 60. Some of the thermal cycling tests of Horton on type 304 stainless steel gave short lives, as well as the low strain tests performed by Kawamoto.[14]

Figure 8 includes fatigue data on types 304 and 316 stainless steel at 815°C. One interesting feature is the relative behavior of type 316 stainless steel in air and vacuum. Danek's[15] data show that this material has considerably better fatigue resistance in vacuum.

Data at temperatures above 800°C are shown in Fig. 9. We normally do not expect that stainless steels will be used at such high temperatures. The data in this figure, however, reveal that on a total strain basis the low-cycle fatigue behavior is no worse than that reported at lower temperatures.

---

[12]M. B. Reynolds, Slow Cycle Strain Fatigue in Thin Wall Tubing, GEAP 3983 (July 1962).

[13]T. F. Balandin, The Comparison of Results of Short- and Long-Term Thermal Fatigue Tests, Zavodskaya Laboratoriya, 29, 746 (June 1963).

[14]M. Kawamoto, T. Tanaka, and H. Nakajima, Study of Effect of Several Factors on Thermal Fatigue,(Report submitted to Am. Soc. Test. Mat. for publication).

[15]G. J. Danek, Jr., H. H. Smith, and M. R. Achter, High Temperature Fatigue in Controlled Environments, NRL-5666 (September 1961).

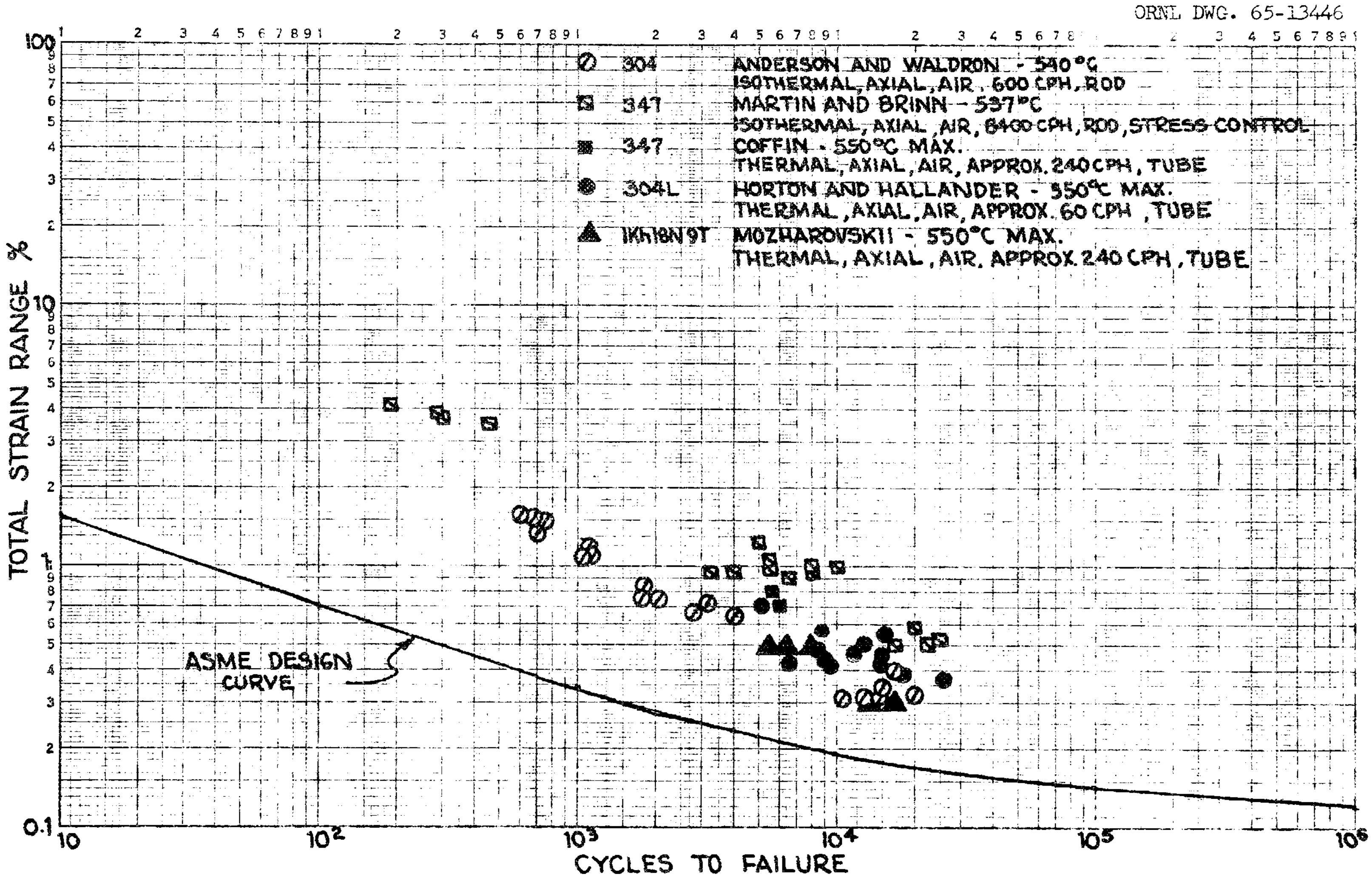

Fig. 4. Fatigue of Stainless Steels Around 550°C.

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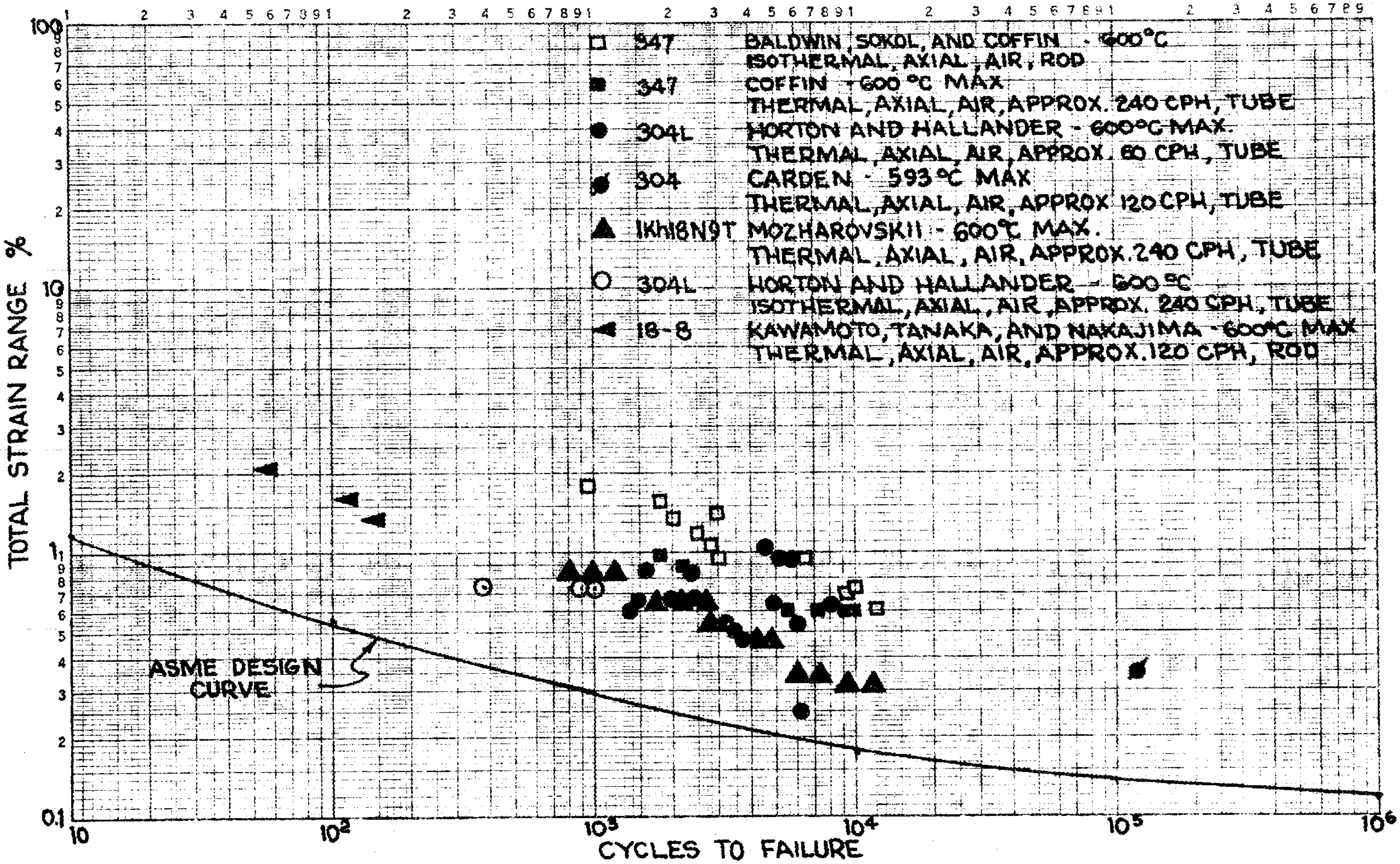

Fig. 5. Fatigue of Stainless Steels Around 600°C.

ORNL DWG. 65-13448

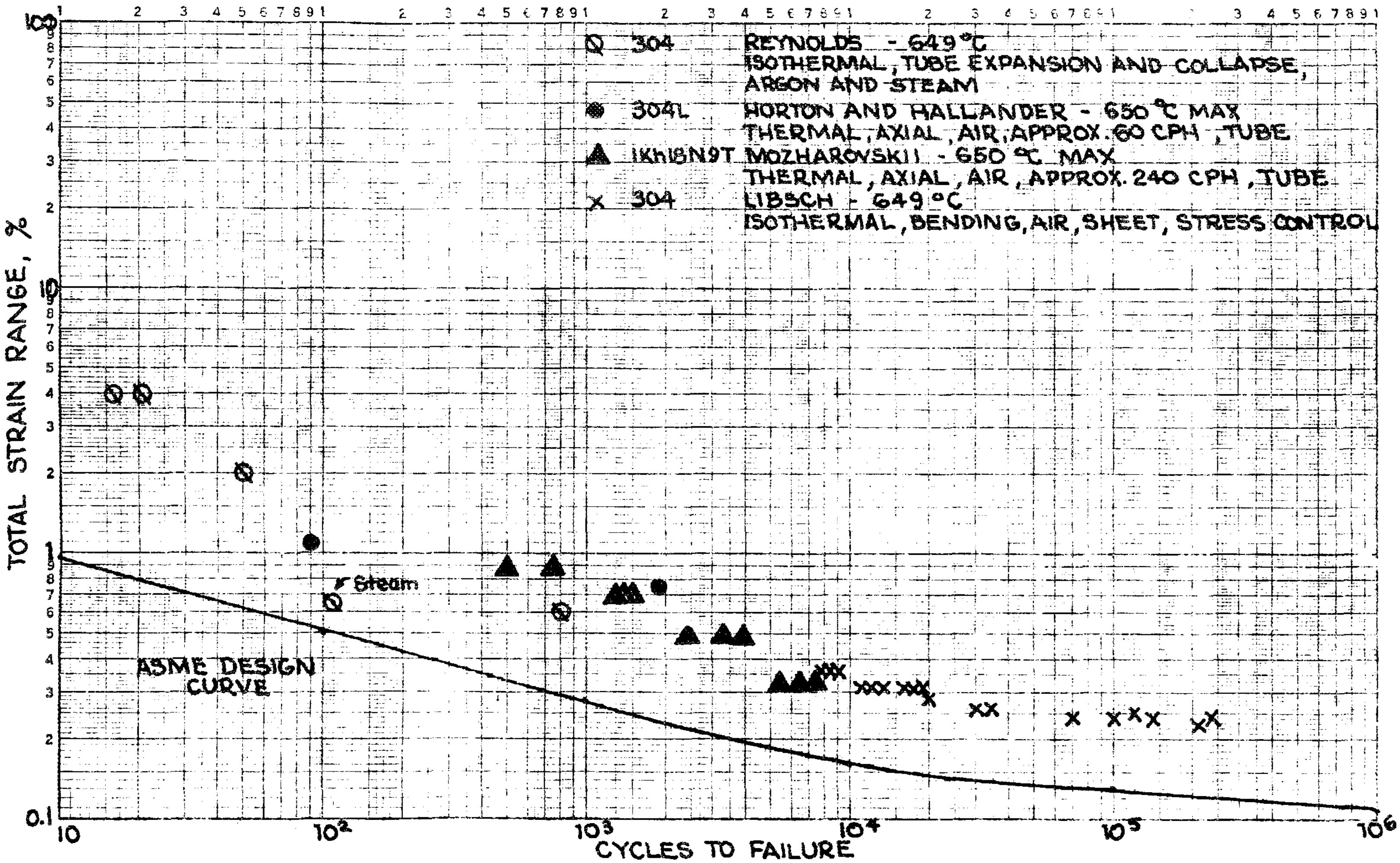

Fig. 6. Fatigue of Stainless Steels Around 650°C.

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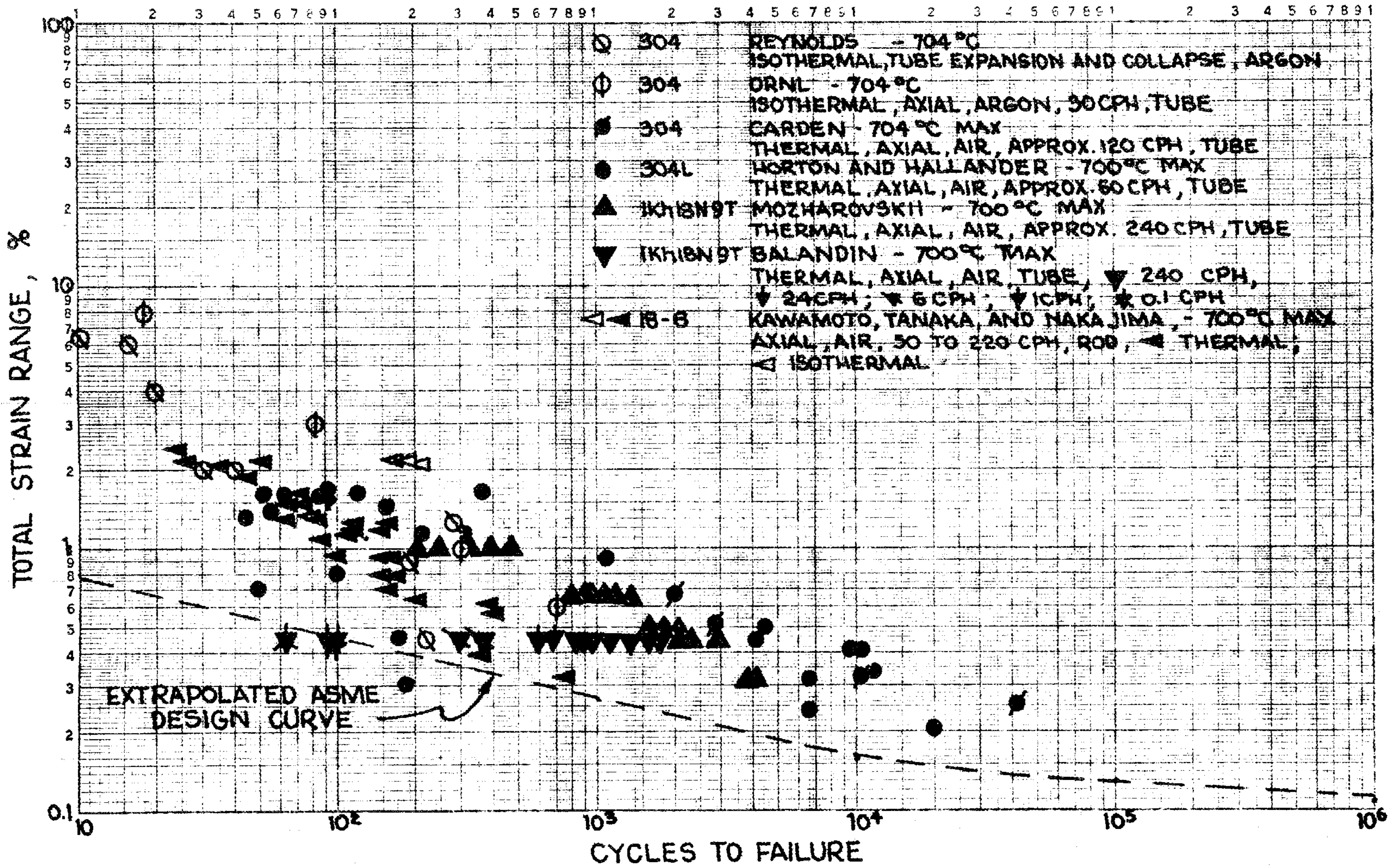

Fig. 7. Fatigue of Stainless Steels Around 700°C.

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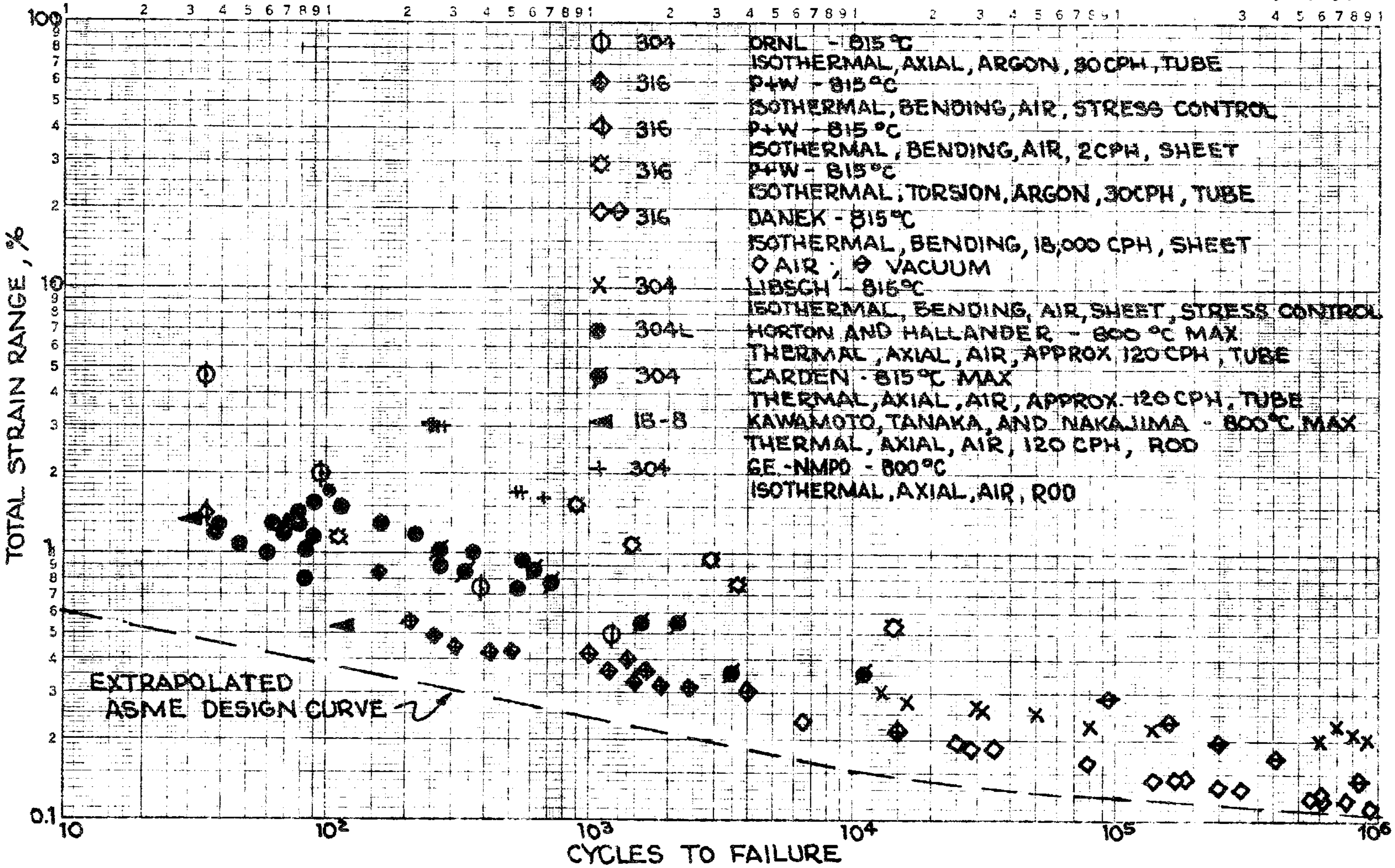

Fig. 8. Fatigue of Stainless Steels Around 800°C.

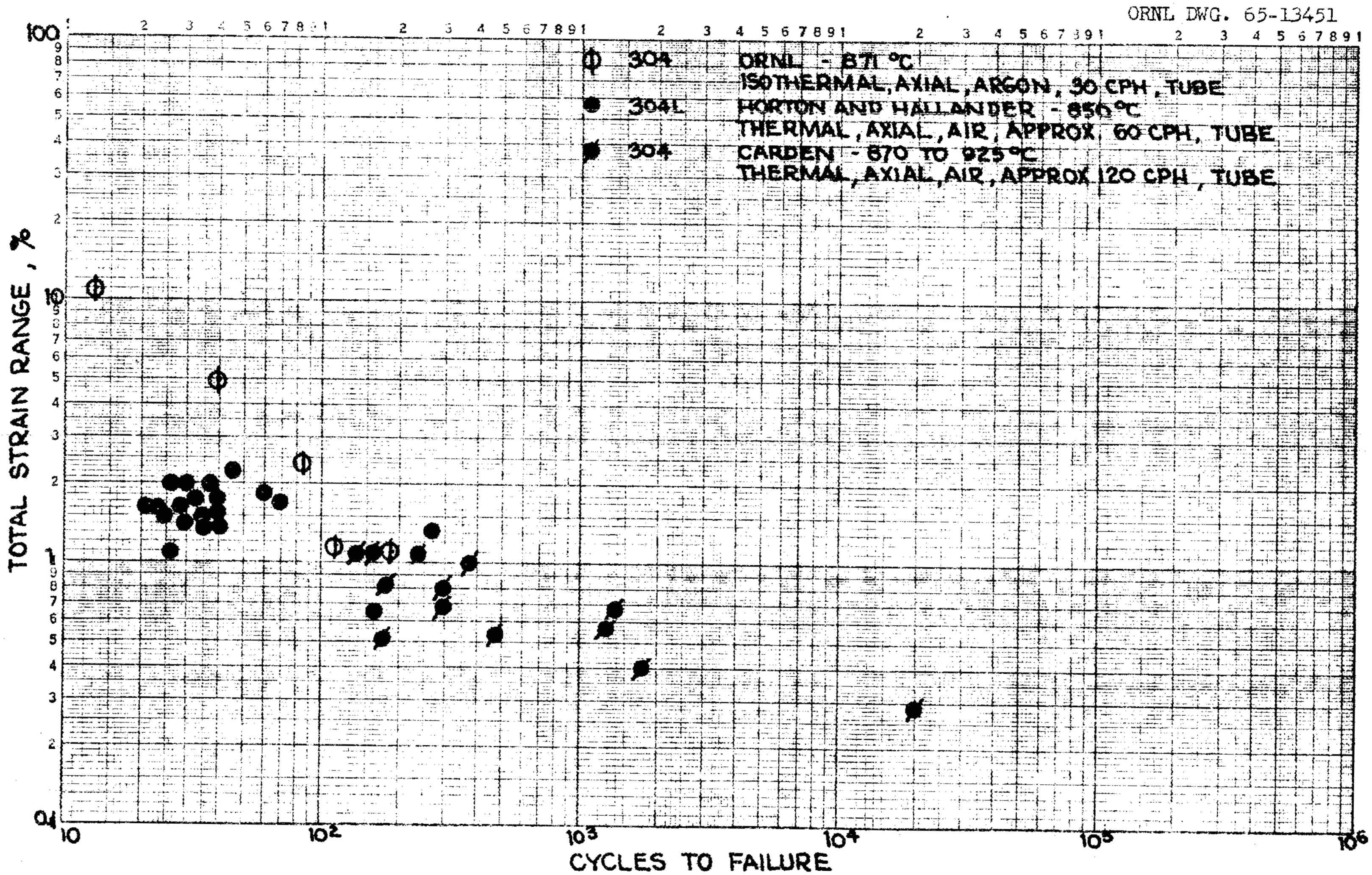

Fig. 9. Fatigue of Stainless Steels Above 800°C.

DISCUSSION

A considerable range of variables is covered by the data reported here. These may be separated into two categories, one pertaining to the testing conditions and the other to specimen considerations. A listing of those which will be discussed is given below.

A. Testing Variables

1. Strain amplitude
2. Temperature
3. Frequency or hold time
4. Control parameter
5. Stress distribution

B. Specimen Variables

1. Material
2. Heat treatment or metallurgical structure
3. Geometry

Strain Amplitude. It is clear that increasing the strain amplitude shortens the fatigue life. In general, Eq. (1) is a fair approximation of the low-cycle fatigue characteristics at elevated temperature, but the constants α and C cannot be evaluated from known engineering properties. Experimental values for α range from 0.3 to 1 and C values differ, in some cases, by more than an order of magnitude from the true fracture strain in tension. It is likely that this problem will be resolved in the near future. Several new theories[16,17] have been advanced recently which assume that low-cycle fatigue is controlled by crack propagation rates through work-hardened material. These theories predict a value of α which depends inversely on the work hardening coefficient. The low work hardening capability at high temperature would indicate larger

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[16] V. Weiss, Analysis of Crack Propagation in Strain-Cycling Fatigue, Fatigue — An Interdisciplinary Approach, p. 179, Syracuse University Press, Syracuse, N. Y. (1964).

[17] J. C. Grosskreutz, A Theory of Stage II Fatigue Crack Propagation, AFML-TR-64-415 (March 1965).

values for α. Another approach, somewhat empirical, has been suggested by Coffin.[18] He shows that, if there is loss in ductility with decreased strain rate in the high-temperature region, the low-cycle fatigue curve may be affected. By developing a parameter to describe the variation in tensile ductility with temperature and strain rate, he was able to correlate high-temperature strain fatigue data at several temperatures.

Temperature. It is evident from the data presented here that the low-cycle fatigue characteristics deteriorate with increasing temperature. The general trend of the data indicates that the "knee" of the fatigue curve is moved toward lower cycles and lower strains as the temperature increases. To a lesser extent, the endurance strain at 10^6 cycles decreases. Any or several of the following phenomena, associated with high temperature, could reduce the strain fatigue resistance.

a. Precipitation of intermetallic phases on grain boundaries.

b. Sigma formation.

c. Void formation.

d. Wedging effects due to grain boundary oxidation.

e. Strain concentration in grain boundaries.

f. Nonuniform strain in the test section due to poor work-hardening characteristics.

Frequency or Hold Time. Frequency or hold time should be important if any of the mechanisms mentioned above are operative. Balandin's data on 1Kh18N9T could be explained on this basis, and perhaps Walker's results on type 316 stainless steel plus columbium. Coffin observed a hold time effect on thermal cycling type 347 stainless steel. Most of the fatigue data reported here, however, span a narrow frequency range and it is difficult to say just how significant frequency of cycling will be in regard to service life.

Control Parameter. With a few exceptions, the restrained thermal cycling data fall short of isothermal strain-fatigue data at temperatures

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[18] L. F. Coffin, Jr., Cyclic Strain and Fatigue Study of a 0.1 pct C — 2.0 pct Mo Steel at Elevated Temperatures, Trans. Met. Soc. of A.I.M.E., 230, 1960 (December 1964).

up to 600°C. This has been explained[19,20] by assuming that actual strains occurring in these tests are higher than the reported values. Horton found that strains in excess of 1% resulted in specimen instability and obvious strain concentration in the buckled region of the gage length. At 650°C and above, restrained thermal cycling data show fairly good correlation with isothermal tests.

Stress-controlled fatigue data for stainless steels are very meager. Available data cover the range from 10^4 to 10^6 cycles, and tend to extrapolate into the strain-controlled data.

Stress Distribution. Stress or strain distribution may have a significant effect on low-cycle fatigue, especially where this distribution might mean the difference between buckling and nonbuckling or between a crack stopping or continuing to propagate. The largest portion of the data reported here has been obtained from axially loaded tests, where the section through which the crack propagates experiences uniform or intensifying strain. In design problems, the peak stress is localized. Hence, a crack must propagate through a section where the strain is reduced in order to produce failure. In this respect, we might expect that strain-fatigue tests in bending might be more applicable. The bending data reported here generally show the best fatigue resistance.

Materials. We might expect some stainless steels to be superior to others. Good tensile ductility is probably a desirable property in the low-cycle range, and high strength is desirable in the high-cycle range. Materials which suffer loss in ductility because of carbide precipitation or sigma formation could be worse in fatigue than weak but nonaging materials. Thus, type 304 stainless steel could prove superior to types 321 and 310 stainless steel. Ignoring the differences in the testing techniques, type 347 stainless steel seems to be the best material up to 600°C, and type 321 stainless steel (1Kh18N9T) is relatively poor.

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[19] T. C. Yen, Thermal Fatigue — A Critical Review, Welding Research Council Bulletin No. 72 (October 1961).

[20] A. E. Carden, Thermal Fatigue — Part I. An Analysis of the Conventional Experimental Method, Proc. Am. Soc. Test. Mat., 63, 735 (1963).

Jumping to 800°C, type 304 stainless steel seems better than type 316 stainless steel, which is a stronger alloy.

Heat Treatment. Horton's data include two different grain sizes and a cold worked material. Although he found little, if any, effect of cold work on thermal fatigue, the fine grained material was superior at high temperatures. Baldwin's data on type 347 stainless steel at 350°C reveal only slight and inconsistent grain size effects, but Coffin's thermal fatigue data on type 347 stainless steel showed a pronounced loss in the low-cycle life for cold worked material. These inconsistencies require rather elaborate explanations.

Geometry. Specimen geometry is critical in generating high-strain fatigue data. The problem of buckling in axial tests has plagued investigators. Thin wall tubular specimens are not stable under axial loads when strains exceed 1%. Under restrained thermal cycling the center of the gage length bulges and the wall thins, while in the end portions the wall sometimes become thicker. Reynolds reports wrinkling (isothermal) of his tubes as a result of plastic expansion and collapse, and the Oak Ridge National Laboratory tests (isothermal) on type 304 stainless steel produced one or two convolutions in axially strained tubes at high strain levels. This problem is particularly acute at high temperatures and is probably associated with poor work hardening characteristics which produce a creep buckling phenomenon. On the other hand, Coffin[21] describes geometric instability at room temperature, and Anderson[22] found similar behavior in aluminum alloys at higher temperatures. The strain concentration and localized ratchet effects thus produced have a significant influence on the low-cycle fatigue behavior, and the fatigue data included in this report should be considered with this in view.

No data are provided in this report pertaining to the low-cycle fatigue properties of weld metal or heat affected zone material. This

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[21] L. F. Coffin, Jr., The Stability of Metals Under Cyclic Plastic Strain, Trans. Am. Soc. Mech. Eng., 82, 671 (1960)

[22] W. F. Anderson and W. Wahl, Results of High-Temperature Strain-Fatigue Tests on Reactor-Grade Aluminum-Base Materials, NAA-SR-4526 (1961).

is an extremely important area for further work. The only protection which the designer has in the prevention of failure in these regions is the safety factor built into the ASME design curves unless – as is commonly the case – he increases the section thickness in the vicinity of the welds or places the welds in regions of low stress.

CONCLUSIONS

1. Data on austenitic stainless steels included in this report indicate that the fatigue design curves presented in Section III of the ASME Boiler and Pressure Vessel Code and Code Case 1331-1 are conservative.

2. Verification of the above statement is needed in regard to sigma forming alloys, especially when these materials are exposed to cyclic strains for long times and at temperatures above 550°C.

3. Considering the factor of safety incorporated into the design curves, there is an appreciable amount of data that falls short of expectations. This should not be of great concern in design work because of the significant differences between the conditions of experimental testing and the service conditions where fatigue analysis is allowed. In experimental testing, crack propagation rates accelerate under intensifying strain fields whereas this should not occur in service applications.

4. Above 600°C the strain-fatigue resistance of stainless steels is drastically reduced. Although the endurance at 10^6 cycles remains near the proportional limit, the endurance at strains around 1% is a factor of 10 to 100 below that which would be expected from Coffin's equation:

$$N_f^{1/2}\epsilon_p = \epsilon_{f/2} \quad .$$

The reason for this is not immediately obvious, but it could be associated with low work hardening characteristics which increase crack propagation rates, time-temperature effects which reduce ductility, or geometric stability problems which produce strain concentrations.

APPENDIX A

ELASTIC MODULII VALUES FOR STAINLESS STEELS

Temperature (°C)	Modulus (psi)
20	27.4
100	27.1
149	26.8
204	26.4
260	26.0
315	25.4
371	24.9
427	24.2
482	23.6
538	23.0
593	22.2
649	21.3

APPENDIX B

INFORMATION PERTAINING TO FATIGUE DATA

AISI Type 347

Reference 23*

Condition: Ann. 1093°C, 1 hr, A.C.

Specimen size: Rod, zero gage length x 3/8 in. or 0.14 in. diam

Loading: Axial

Control: Plastic strain range at zero load

Frequency: 400 cph, 100 cph, or variable according to strain rate or strain range.

Temperatures: Room

Atmosphere: Air

Reference 7

Condition: Four different heat treatments to vary grain size from ASTM No. 2 to 7. Data reported here pertain to 1100°C, 5 min., A.C. giving ASTM No. 7.

Analysis: Six different heats. The following pertains to data reported here:

C	Ni	Cr	Mn	Li	Cl	Ta	P	S
0.055	11.1	17.9	1.5	0.45	0.73	0.025	0.034	0.027

Specimen size: Rod, 1/2 in. gage length x 3/16 in. diam

Loading: Axial

Control: Total extension limits

Atmosphere: Air

Reference 24*

Condition: Ann. 1093°C, 15 min, W.Q.

Specimen size: Rod, 1/2 and 1 in. gage length x 1/4 in. diam

Loading: Axial

Control: Stress amplitude, strain recorded

Frequency: 140 cpm

Temperature: 537°C

Atmosphere: Air

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*See page 35 for reference.

Reference 9

Condition:	Ann. 1100°C, A.C., and cold worked in torsion or tension
Specimen size:	Tubular, 2 in. gage length x 0.540 in. OD x 0.020 wall
Loading:	Axial produced by restrained thermal cycling
Control:	Temperature limits and hold time
Frequency:	Approximately 240 cph with hold times up to 3 min.
Temperatures:	Maxima ranging up to 600°C, minima down to 150°C. Mean 250, 350, and 450°C
Atmosphere:	Air

Reference 25*

Condition: Ann. 1100°C, 2 hr, W.Q.

Analysis:

C	Mn	Si	P	S	Ni	Cr	Cb
0.065	0.79	0.35	0.009	0.024	11.97	18.1	0.78

Mechanical Properties:

Temp.	UTS	Y.S.	El%	R.A.
Room	80,000	32,000	62.5	71.5

Specimen size:	Tubular, 1.2 in. gage length x 0.47 in. OD x 0.040 wall
Loading:	Axial produced by restrained thermal cycling. Also combined thermal and mean loading
Control:	Temperature limits and mean stress
Frequency:	1 cpm
Temperature:	400°C mean
Atmosphere:	Air

AISI Type 304, 304L, and 304 ELC

Reference 12 (304)

Condition:	Not specified
Specimen size:	Tubular, 3 in. gage length x 1.25 OD x 0.016 wall
Loading:	Alternate internal and external pressure
Control:	Extension limits determined by mandrel size
Temperature:	649, 704°C
Atmosphere:	Argon, steam

Reference 26*(304)

Condition: Ann. 1038°C, 1 hr, A.C.

Specimen size: Tubular, 1 in. gage length x 0.963 OD x 0.060 wall

Loading: Axial

Control: Total extension limits

Frequency: 30 cph

Temperature: 704, 815, and 871°C

Atmosphere: Air

Reference 8 (304 and 304L)

Condition: Three conditions for 304L: 1) cold worked, 2) 1038°C, 2 hr, and 3) 1149°C, 2 hr. Single condition for 304: 1038°C, 2 hr

Analysis:

	C	Mn	Li	P	S	Cr	Ni
304	0.05	0.88	0.50	0.028	0.011	18.71	9.84
304L	0.018	1.32	0.65	0.009	0.011	18.22	10.51

Specimen size: Tubular, 2 in. gage length x 0.64 OD x 0.02, 0.03, or 0.04 wall

Loading: Axial produced by restrained thermal cycling. Some isothermal test axially loaded by thermal cycling restraining columns.

Control: Rate of temperature change and temperature limits

Frequency: Variable around 1 cpm plus hold times between 0 and 60 sec.

Temperatures: Maxima up to 900°C, minima down to 100°C, mean of 400 and 600°C

Atmosphere: Air and argon

Reference 27* (304)

Condition: Mill anneal

Analysis:

C	Mn	Li	P	S	Cr	Ni
0.06	0.83	0.66	0.02	0.014	18.48	9.47

Mechanical properties:

Temp.	UTS	Y.S.	% El	% R.A.
Room	83,000	37,700	62	----

Specimen size: Tubular, 2 in. gage length x 0.64 OD x 0.040 wall

Loading: Axial produced by restrained thermal cycling

Control:	Temperature limits
Frequency:	Variable around 120 cph
Temperature:	Maxima vary from 482 to 926°C, minima from 100 to 740°C, mean values from 482 to 815°C
Atmosphere:	Air

Reference 28* (304)

Condition: Cold rolled and annealed

Analysis:

C	Mn	Li	P	S	Cr	Ni
0.061	0.87	0.60	0.021	0.011	18.76	9.53

Specimen size:	Sheet
Loading:	Bending
Control:	Stress amplitude
Frequency:	Not specified
Temperature:	649, 732, 815°C
Atmosphere:	Air

Reference 29* (304)

Condition:

Analysis:

C	Mn	P	S	Cr	N
0.034	0.61	0.03	0.023	19.0	9.0

Specimen size:	Rod, 1/2 in. gage length x 1/4 in. diam
Loading:	Axial
Control:	Plastic strain range determined at zero load
Frequency:	Variable from 0.6 to 60 cpm
Atmosphere:	Air

Reference 6 (304)

Condition: No specified

Analysis:

	C	Mn	P	S	Li	Cr	Ni
Heat A –	0.08	0.46	0.032	0.016	0.17	17.48	8.75
Heat B –	0.10	0.58	0.031	0.016	0.15	17.95	7.95

Mechanical properties:

Temp.	UTS	Y.S.	% El	% R.A.
Room	101,000	38,500	79	81.0
300	75,000	21,000	47	70.5
500	70,000	20,500	45	66.0

Specimen size: Tapored rod, 0.15 in. minimum diameter

Loading: Deflection limits

Frequency: 0.5 cpm

Temperature: 20, 300, and 500°C

Atmosphere: Air

Reference 14 (18/8)

Condition: Not specified

Analysis:

C	Li	Mn	S	P	Ni	Cr	Mo
0.065	0.85	0.93	0.005	0.032	8.9	18.7	0.14

Mechanical properties:

Temp.	UTS	Y.S.	% El	% R.A.
Room	90,000	32,900	65	71.2

Specimen size: Rod, variable diameter and length

Loading: Axial produced by restrained thermal cycling and mechanical load

Control: Temperature limits. Also degree of restraint was varied to produce different strains at the same temperature limits

Frequency: 1 to 4 cpm

Temperature: Maxima vary from 500 to 800°C. Minima from 100 to 300°C

Atmosphere: Air

Reference 30* (304)

Condition: Mill annealed

Analysis:

C	P	S	Cr	Ni	Cr
0.039	0.026	0.012	18.83	8.99	0.19

Mechanical properties:

Temp.	UTS	Y.S.	% El	% R.A.
Room	84,000	33,500	72	70
540°C	55,000	20,000	40	60

Specimen size: Rod, 1/2 in. gage length x 0.188 diam

Loading: Axial

Control: Total extension limits

Frequency: 10 cpm

Temperatures: Room, 540°C

Atmosphere: Air

Reference 5 (304 ELC hard, 304 ELC)

Condition: Annealed, cold drawn

Analysis:

C	Mn	P	S	Si	Cr	Ni
0.026	0.45	0.03	0.014	0.40	18.67	8.50

Mechanical properties:

	UTS	Y.S.	% El	% R.A.
Ann.	108,000	37,000	---	74.3
Hard	138,000	108,000	---	68.8

Specimen size: Rod, zero gage length, 1/4 in. diam

Loading: Axial

Control: Diametric strain range

Frequency: Up to 30 cpm

Temperature: Room

Atmosphere: Air

AISI Type 316

Reference 15

Condition: Not specified

Specimen size: Sheet, zero gage length x 1/2 in. x 0.050 in.

Loading: Bending

Control: Deflection limits

Frequency: 300 cpm

Temperature: 815°C

Atmosphere: Air and vacuum

Reference 31*

Condition: Not specified

Specimen size: 1) Rotating beam not specified (rod), 2) plate in bending not specified, and 3) torsion, tubular 2 3/8 in. g.l. x 3/8 in. OD x 0.070 wall

Loading: 1) bending (rotating beam), 2) bending over and avil, 3) torsion stress

Control:	1) stress amplitude, 2) total deflection limits, and 3) total twist limits
Frequency:	1) not specified, 2) probably 2 cph, and 3) 1 1/2 cpm
Temperature:	815°C
Atmosphere:	1) air, 2) air, and 3) argon

Reference 11 (316 and Cb)

Condition: Ann. 1052°C, 10 hr S.C. + 871, 10 hr F.C.

Analysis:

C	Mn	S	Si	Cr	Mo	Ni	Cb + Ta
0.08	0.84	0.021	0.89	14.86	2.0	14.34	0.95

Specimen size:	Rod, 0.7 in. gage length x 3/16 in. diam
Loading:	Axial
Control:	Total extension limits
Frequency:	12 hr hold in tension
Temperature:	510°C
Atmosphere:	Air

AISI Type 321

Reference 10 (1Kh18N9T)

Condition:	Not specified
Specimen size:	Tubular, 2.35 in. gage length x 0.5 in. OD
Loading:	Axial produced by restrained thermal cycling
Control:	Temperature limits. Also the degree of restraint was varied to produce different strains for the same temperature limits
Frequency:	Approximately 4 cpm
Temperature:	Maxima from 100 to 200°C, mean from 250 to 400°C
Atmosphere:	Air

Reference 13 (1Kh18N9T)

Condition:	Not specified
Specimen:	Tubular
Loading:	Axial produced by restrained thermal cycling
Control:	Temperature limits and hold time

Frequency:	From 4 cpm to 0.1 cph
Temperature:	700°C maximum, 100°C minimum
Atmosphere:	Air

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