NRL Report 6489

High-Temperature Vacuum Fatigue Testing of Type 316 Stainless Steel and Inconel X With a Resonance-Type Machine

H. H. Smith, P. Shahinian, and M. R. Achter

High Temperature Alloys Branch
Metallurgy Division

March 27, 1967

NAVAL RESEARCH LABORATORY
Washington, D.C.

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

CONTENTS

Abstract	ii
Problem Status	ii
Authorization	ii
INTRODUCTION	1
EXPERIMENTAL DETAILS	1
RESULTS	2
Type-316 Stainless Steel	2
Inconel X	3
DISCUSSION	6
ACKNOWLEDGMENT	10
REFERENCES	10

ABSTRACT

A new resonance-type flexural fatigue machine has been used to test Inconel X, a low damping capacity material, and Type-316 stainless steel, a high damping material, at 500° and 800°C. A comparison was made of the reproducibility of the data obtained by various test procedures with smooth and notched specimens. Observations were made of the type of cracking in these materials. The progression of cracking appeared to be reflected in resonant frequency changes during the test. The reproducibility of the fatigue data, in particular of the Inconel X, which has a sharp resonance, is sufficiently good to permit distinguishing environmental effects, the main purpose for which the equipment was designed.

PROBLEM STATUS

This report completes one phase of the problem; work on other phases of the problem is continuing.

AUTHORIZATION

NRL Problem M01-09
Project RR 007-01-46-5407

Manuscript submitted September 13, 1966.

HIGH-TEMPERATURE VACUUM FATIGUE TESTING OF TYPE 316 STAINLESS STEEL AND INCONEL X WITH A RESONANCE-TYPE MACHINE

INTRODUCTION

Previous studies of fatigue in vacuum at elevated temperatures were made with a flexural machine which required manual tuning to the resonant frequency (1-3). Although the equipment proved satisfactory for soft materials of high damping capacity, it was found to have shortcomings for hard materials of low damping capacity which have a sharp resonance peak. Hard alloys have such a sharp resonance peak that it was difficult to tune and hold to the correct frequency manually long enough to generate a visible crack. In order to improve the operation of the machine and extend its capability, modifications have been made to automatically maintain the vibration of the specimen at its resonant frequency (4).

It was the primary purpose of the investigation to explore the capabilities of this new resonance-type machine using Type-316 stainless steel and Inconel X. We examined in detail various operating procedures and conditions including types of specimen to determine the characteristics of this method of testing. In addition to selecting experimental methods for optimum performance, we examined the reproducibility of the data generated. Also, the change in resonant frequency of vibration during fatigue at elevated temperature was recorded and its possible association with structural changes in the material was considered.

EXPERIMENTAL DETAILS

Details of the construction and operation of the machine are described elsewhere (4). Briefly, as shown schematically in Fig. 1, the specimen is driven in reverse bending by two external electromagnets. A regenerative drive incorporating a capacitance pickup is used to keep the specimen assembly vibrating at resonance. Automatic devices record the change in frequency as the test progresses and interrupt it when the desired frequency change has been reached. Precise amplitude control is achieved by feedback loops incorporating two movable contacts and all solid state circuits. The variation in amplitude for short periods is about 0.25% and for extended periods less than 0.5%. Provision is made to operate the equipment with either one or two contacts (one and two channel control). The choice of the method used is dictated by the characteristics of the test material, as will be described in experiments comparing one and two channel control.

Details of the specimen geometry have been reported elsewhere (1). Sheet specimens with a radiused reduced section of 0.187-in. minimum width, having a thickness of 0.1100 in. for the Type-316 stainless steel and 0.0937 in. for the Inconel X were used in this investigation. For a study of the behavior of notched specimens in this equipment a shallow notch was made in Inconel X specimens either by grinding (90-deg, 0.001-in.-root-radius notch) or by spark cutting. The stainless steel was vacuum annealed for 1 hr at 1066°C and the Inconel X was given a heat treatment of 2 hr at 1149°C, 24 hr at 843°C, and 20 hr at 704°C. Prior to testing, all smooth and notched specimens were electropolished except those in which the notch was introduced by spark cutting.

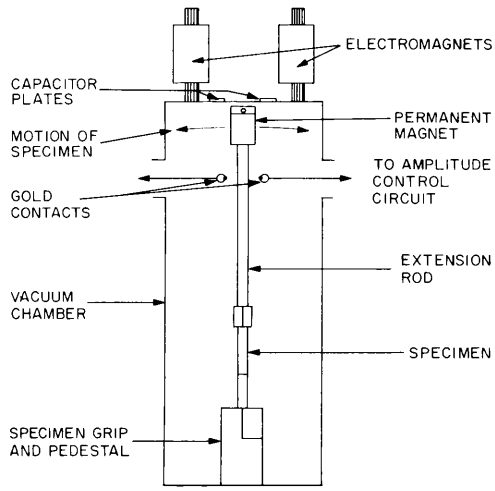


Fig. 1 - Main elements of the resonance-type fatigue machine

Both materials were vibrated at approximately 10 cps at 500° and 800°C in a vacuum of about 10^{-6} torr. At a resonant frequency decrease of usually 0.5 or 0.6 cps, failure was considered to have occurred and the test was automatically terminated. Measurements of the bending strain at temperature were made on smooth specimens in air by an optical method (2). For notched specimens a nominal strain is recorded which corresponds to the strain on a smooth specimen whose thickness is equal to that at the minimum notch section. To check reproducibility several tests were run at the same temperature and strain.

RESULTS

Type-316 Stainless Steel

Type-316 stainless steel was chosen as representative of relatively soft materials of high damping capacity. At 500°C it showed a tendency to sag to one side or the other as a result of creep when the amplitude of vibration was controlled from one side. With two-channel control, however, the variation of amplitude was within the range 0.25 to 0.5% cited above. The fatigue lives at 500° and 800°C, taken as the cycles to produce a 0.6-cps reduction in frequency, are listed in Table 1 for tests using two-channel control. At this frequency change a crack had propagated almost completely through the specimen cross section, and fracture was imminent; thus the time approximates very closely the life. A greater scatter is evident in the data obtained at 500° than at 800°C. This may be due, however, to the longer duration of the tests at the lower temperature and not to the effect of temperature itself. Standard deviations determined from the small samples indicate a smaller dispersion at the higher temperature, but the difference might not be significant.

Table 1
Fatigue Life of Smooth Specimens of Type-316 Stainless Steel (Annealed) Using Two-Channel Operation

Temp. (°C)	Total Strain (%)	Fatigue Life (cycles) $\Delta f = 0.6$ cps
500	0.26	1.76×10^6
		2.71×10^6
		2.13×10^6
		1.54×10^6
		mean = 2.04×10^6
		s* = 0.51×10^6
800	0.15	3.19×10^5
		2.77×10^5
		3.04×10^5
		2.20×10^5
		2.75×10^5
		mean = 2.79×10^5
		s* = 0.378×10^5

*s = standard deviation.

During the fatigue test the structural changes that take place in the material should be reflected in the resonant frequency of vibration. Recorded curves of the period of vibration, Fig. 2, show that the shape of the frequency versus time curve is not the same for the stainless steel at 500° as it is at 800°C. The large increase in frequency (shown as decrease in period) at the beginning of the test at 500°C is attributed to strain hardening. Prominent slip lines were formed on the specimen surface at this temperature, as seen in Fig. 3. Stainless steel with a prior cold reduction of 50% in thickness did not exhibit the large rise in frequency at 500°C but showed only a small increase, Fig. 4. Since the deformation during fatigue is of a different type than that produced by rolling, there might possibly be a small additional increase in hardness during the test. As shown in Fig. 2, at 800°C this strain hardening effect is very small owing, presumably, to concurrent rapid recovery. A decrease in the frequency, as illustrated by the final portions of the curves, is caused by the relatively rapid growth of cracks. A significant drop in frequency takes place in the final 10% of the test at 500°C and the final 20% at 800°C. Frequency versus time curves were nearly identical for multiplicate tests run under the same conditions.

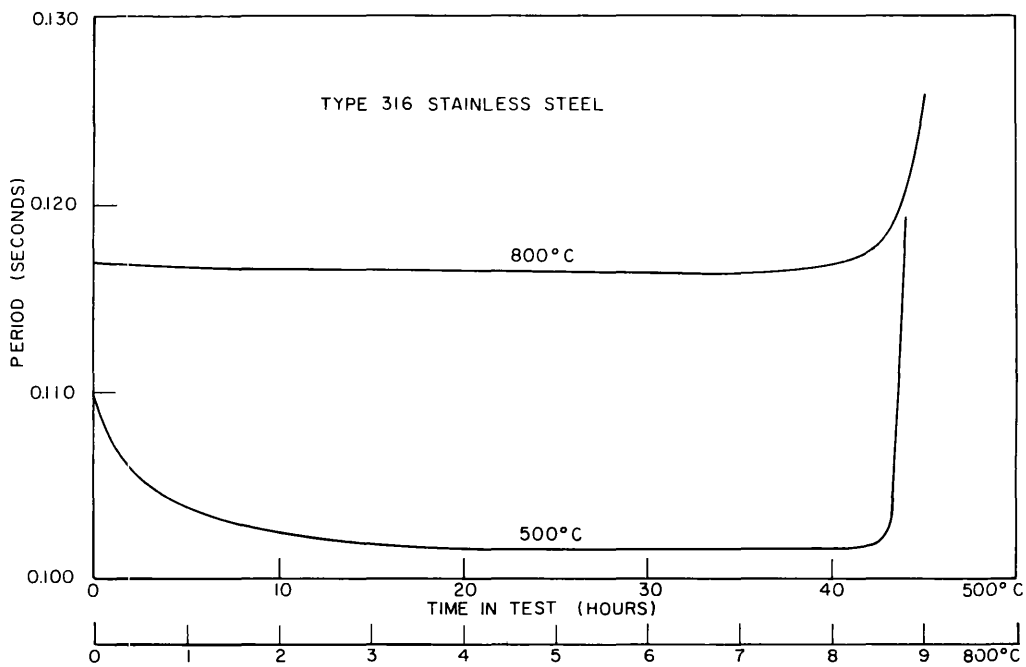


Fig. 2 - Resonant frequency changes during fatigue of Type-316 stainless steel at 500°C (0.26% strain) and 800°C (0.15% strain)

In this material, essentially a single crack forms and leads to failure, as shown in Fig. 5. The cracking followed a predominantly transgranular path at both temperatures, but the cracks were straighter at 500°C.

Inconel X

Inconel X was chosen as representative of hard materials with low damping capacities — of the type which was difficult to tune to resonance manually. With the new equipment there was no difficulty in maintaining the frequency at resonance. Because of its

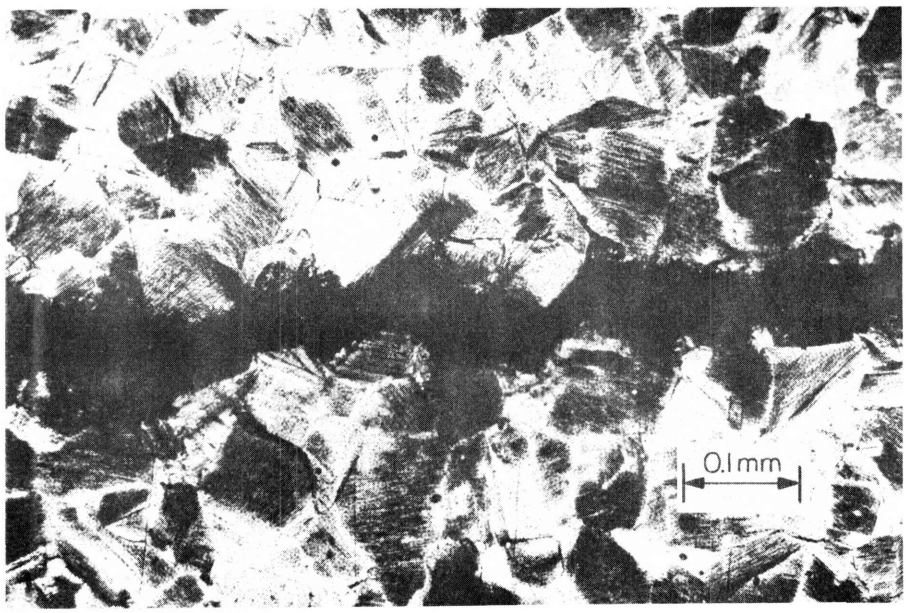


Fig. 3 - Surface of stainless steel fatigue tested at 500°C and 0.26% strain (200X)

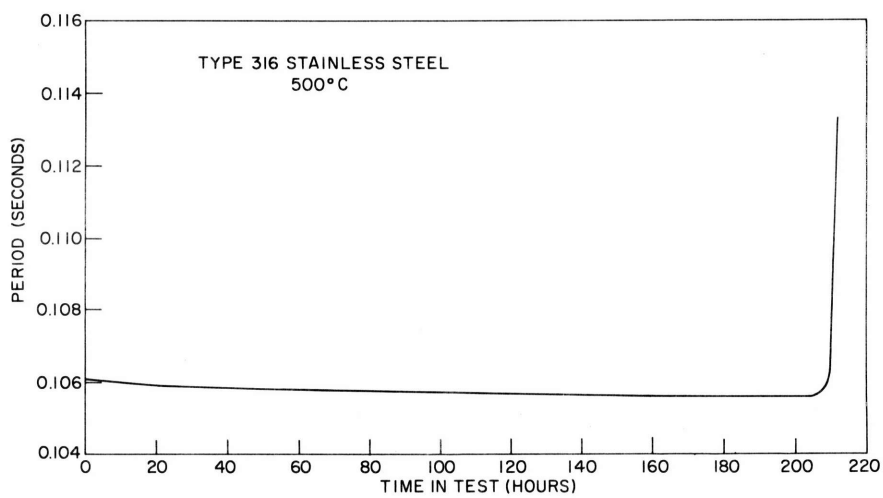
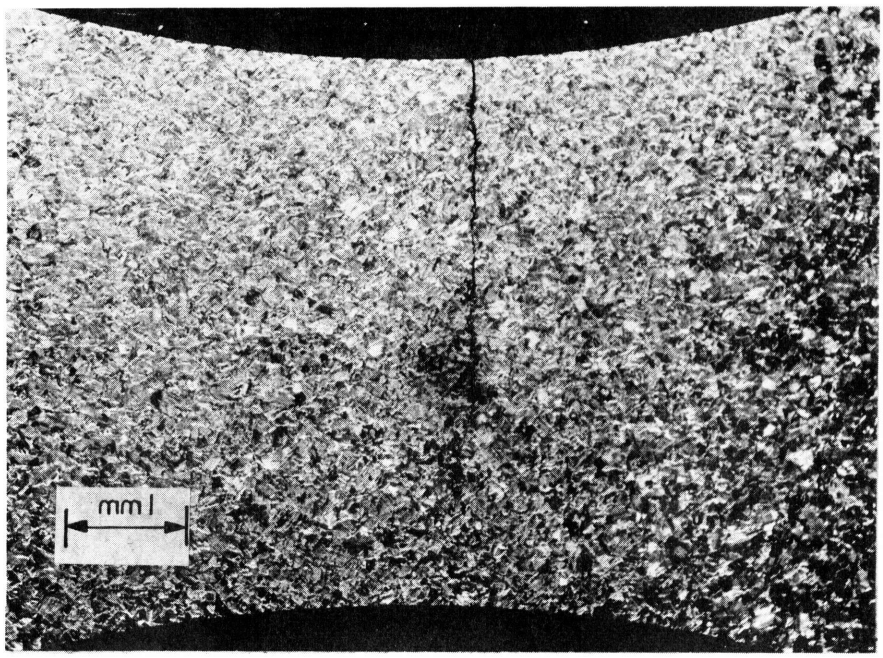


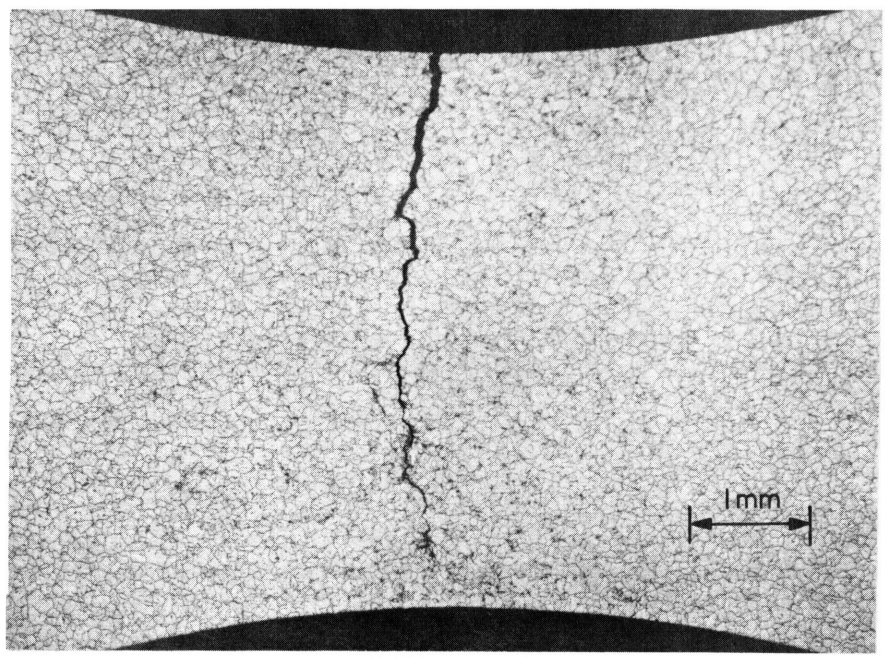
Fig. 4 - Resonant frequency changes during fatigue of cold worked stainless steel at 500°C and 0.26% strain

good creep resistance at elevated temperatures it was possible to operate with one-channel control, even at 800°C.

Smooth Specimens — Although it has been determined that satisfactory results can be achieved with the simpler method using one channel, several tests were run at 500°C to determine the characteristics of two-channel control on hard materials. It was found that the introduction of fatigue damage caused an unbalance of the currents to the two magnets and termination of the test before the desired frequency changes had been reached. It was then possible to continue with one channel until the desired frequency change was achieved,



(a) At 500°C



(b) At 800°C

Fig. 5 - Surfaces of Type-316 stainless steel fatigue specimens showing cracks that had developed after a 0.6-cps change in frequency (20X)

Table 2A. However, the reproducibility is not as good as when only one channel is used for the entire life.

Since under one-channel control, only one electromagnet is used to excite the vibration, one surface of the specimen is under slightly greater tensile strain than the other. The circuits are designed so that the high strain side is facing away from the one control contact being used. Usually, it is the high strain side on which cracking is more severe. Therefore, when the specimen assembly begins to bend over slightly, about 1%, in the final 10% of its life, the bending strain imposed on the surface remains constant.

At 500°C, the cracks were always initiated where expected, and, consequently, the reproducibility, Table 2B, was very good. At 800°C, however, sometimes the cracks appeared on the low strain side and produced an increase in strain amplitude. When this happened, Table 2C, the life was significantly reduced. In an attempt to prevent this uncontrolled cracking, the edges on the low strain side of two specimens were rounded off. But even here, one of them unexpectedly failed on the low strain side.

To prevent the increase of the amplitude, even if the cracks are initiated on the low strain side, the equipment was modified so that it could be operated with one channel which could take its signal from either contact. Of the five specimens tested in this manner, Table 2D, only one failed in the unexpected manner, so that a conclusive assessment of the technique was not possible. It is, however, felt that the prevention of the overamplitude should result in a reduction of scatter.

Curves showing the frequency change during the tests for Inconel X, Fig. 6, were different from those for the stainless steel in that the decrease in frequency began much earlier. The cause for the initial rapid frequency drop at 800°C is not known, but it could be due to an aging reaction in the material.

In contrast to the type of cracking in stainless steel, in which a single crack was generated, numerous cracks formed in the reduced section of the Inconel X, as shown in Fig. 7. The cracks which developed at 500°C were sharper than those at 800°C.

Notched Specimens — As shown in Table 2E, the introduction of a ground notch did not appear to affect the reproducibility significantly. When, however, the notch was introduced by spark cutting, the data became erratic. With this type of metal removal the microstructure adjacent to the notch was altered to an appreciable depth by the cutting operation, as shown in Fig. 8. Perhaps this disturbance introduced by the cutting operation, as used here, was variable and contributed to the large scatter in data. In any case the spark cutting technique disturbed the metal surface considerably more than did the grinding operation.

DISCUSSION

Both stainless steel and Inconel X were fatigue tested in the resonance-type machine without difficulty, except for the 800°C tests of Inconel X. In these tests, some of the specimens cracked predominantly on the low strain side, and the resulting short fatigue lives contributed to greater scatter than exhibited in the other groups of tests. Even so, the fatigue lives varied only by a factor of approximately 2. The reason for this abnormal behavior is not known, but apparently under these test conditions the small difference in surface strain between the two sides is less influential than other factors in controlling crack initiation.

In any case the reproducibility of these fatigue data is sufficiently good to permit distinguishing environmental effects, the main purpose for which the equipment was designed. Here, the variation in fatigue lives is generally less than a factor of 2, whereas

Table 2
Fatigue Life of Inconel X

Temp. (°C)	Total Strain (%)	Lot	Δf (cps)	Fatigue Life (cycles)		
A. Smooth Specimens						
				Two Channels	One Channel	Total
500	0.23	M1	0.25	2.74×10^6	0.94×10^6	3.68×10^6
				2.04×10^6	0.78×10^6	2.82×10^6
				0.41×10^6	1.17×10^6	1.58×10^6
B. Smooth Specimens: One Channel, One Contact						
500	0.23	M2	0.5	1.22×10^6		
				1.12×10^6		
				1.04×10^6		
				1.01×10^6		
				0.71×10^6		
				1.15×10^6		
				mean = 1.04×10^6	s* = 0.179×10^6	
C. Smooth Specimens: One Channel, One Contact						
800	0.16	M2	0.5	1.16×10^6		
				0.74×10^6		
				0.54×10^6†		
		M2a		0.65×10^6†		
				1.28×10^6‡		
				mean = 0.874×10^6	s = 0.327×10^6	
D. Smooth Specimens: One Channel, Two Contacts						
800	0.16	M2b (0.048-in. width)	0.5	0.89×10^6		
				1.45×10^6		
				1.09×10^6		
				1.23×10^6		
				0.82×10^6†		
				mean = 1.10×10^6	s = 0.256×10^6	
E. Notched Specimens: One Channel, One Contact						
				(0.002-in. ground notch)		
500	0.23	M2	0.5	6.11×10^5		
				5.26×10^5		
				6.41×10^5		
				9.37×10^5		
				mean = 6.79×10^5	s = 1.79×10^5	
				(0.005-in. ground notch)		
	0.22	M1	0.11	4.58×10^5		
				4.63×10^5		
				5.66×10^5		
				(0.005-in. spark cut notch)		
	0.22	M1	0.5	32.6×10^5		
				1.45×10^5		
				0.89×10^5		

*s = standard deviation.
†Cracked on the low strain side.
‡Rounded edges.

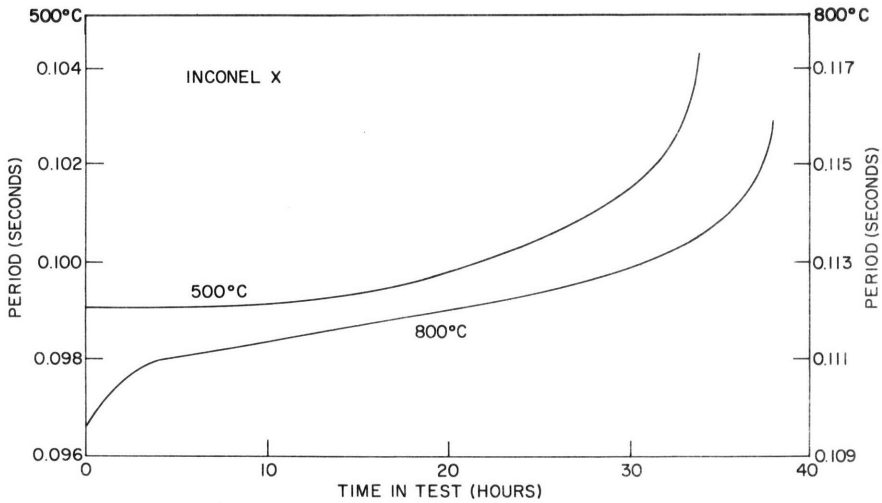
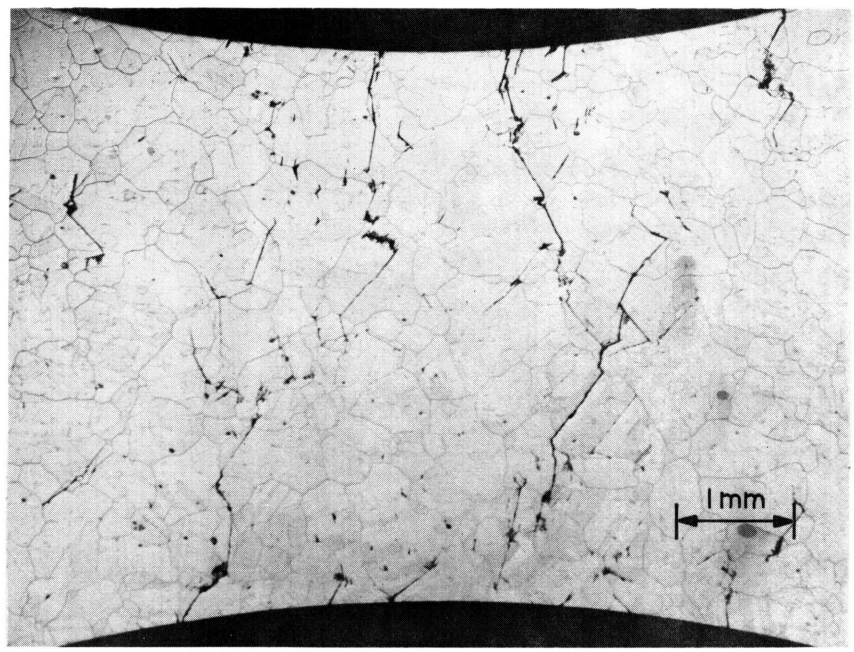
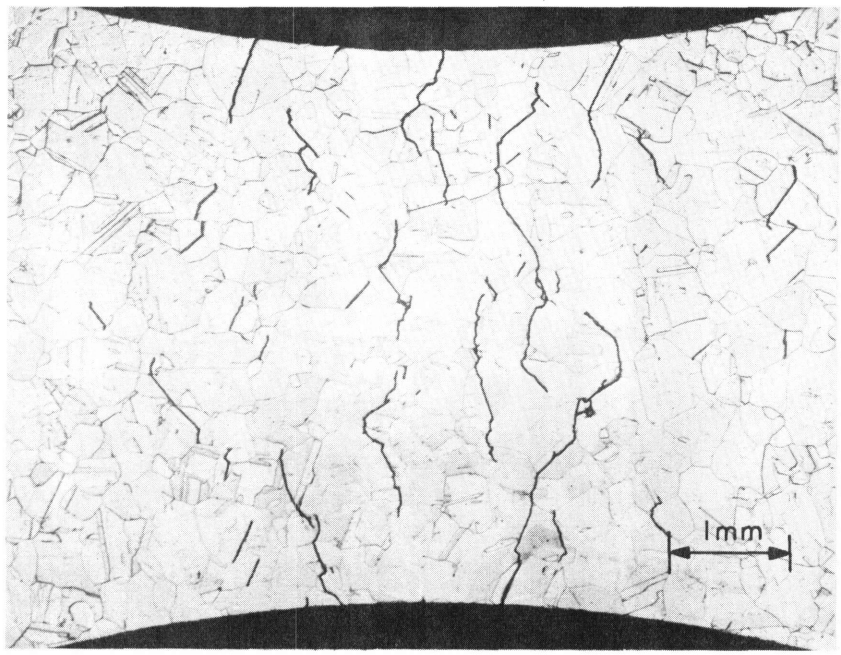


Fig. 6 - Resonant frequency changes during fatigue of Inconel X at 500°C (0.23% strain) and 800°C (0.16% strain)



(a) Fatigued at 500°C

Fig. 7 - Multiple cracks in surfaces of Inconel X fatigue specimens after a frequency change of 0.5 cps (20X) (continued)



(b) Fatigued at 800°C

Fig. 7 - Multiple cracks in surfaces of Inconel X fatigue specimens after a frequency change of 0.5 cps (20X)

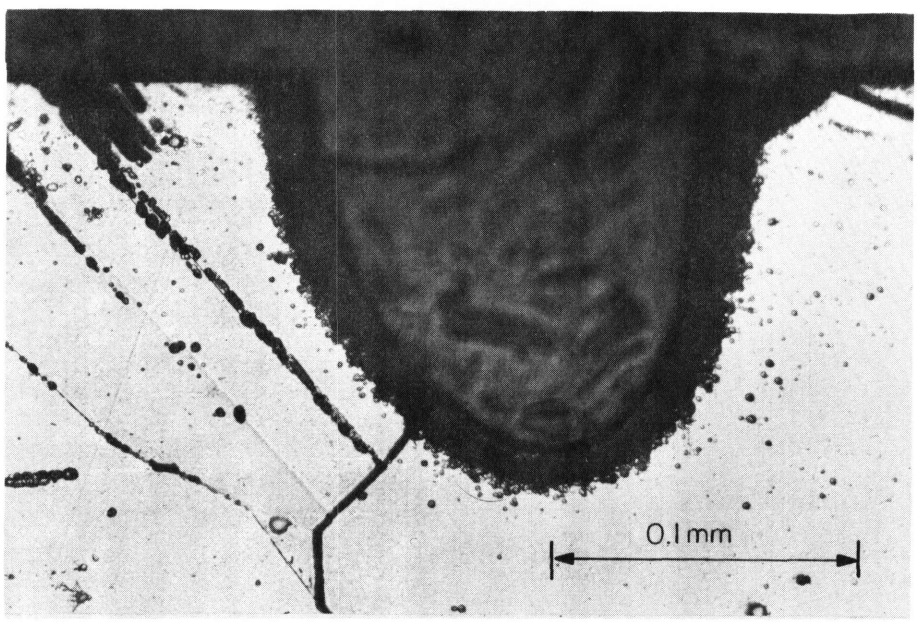


Fig. 8 - Microstructure of notch section made by spark cutting showing heat affected layer (500X)

environment has been shown to produce a change of as much as a factor of 25 (2) or even 100 (5). We believe the reproducibility is adequate for most purposes and compares favorably with that of most fatigue data.

ACKNOWLEDGMENT

The authors appreciate the assistance of A. C. Yingling in the test program and of D. H. Price and A. R. Donaldson in the metallographic work. They are also indebted to J. P. Grimes and P. C. Ryan for examining the statistical aspects of the data.

REFERENCES

1. Danek, G.J., Jr. and Achter, M.R., "A High-Temperature, Vacuum, and Controlled-Environment Fatigue Tester," Am. Soc. Testing and Mats. Bulletin 234, Dec. 1958, p. 48

2. Danek, G.J., Jr., Smith, H.H., and Achter, M.R., "High-Temperature Fatigue and Bending Strain Measurements in Controlled Environments," Proceedings, Am. Soc. Testing and Mats., Vol. 61, 1961, p. 775

3. Achter, M.R., Danek, G.J., Jr., and Smith, H.H., "Effect on Fatigue of Gaseous Environments under Varying Temperature and Pressure," AIME 227:1296 (Dec. 1963)

4. Achter, M.R., Smith, H.H., Riley, R.J., and Stegman, R.L., "Flexural Fatigue Machine for High Temperature Operation at Resonance in Vacuum," Rev. Sci. Instr. 37(No. 3): 311 (Mar. 1966)

5. Snowden, K.U., "The Effect of Atmosphere on the Fatigue of Lead," Acta Metallurgica 12:295 (Mar. 1964)

Security Classification

DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author) Naval Research Laboratory Washington, D.C. 20390	2a. REPORT SECURITY CLASSIFICATION Unclassified 2b. GROUP

3. REPORT TITLE

HIGH-TEMPERATURE VACUUM FATIGUE TESTING OF TYPE 316 STAINLESS STEEL AND INCONEL X WITH A RESONANCE-TYPE MACHINE

4. DESCRIPTIVE NOTES (Type of report and inclusive dates)

A final report on one phase of a continuing problem.

5. AUTHOR(S) (First name, middle initial, last name)

Smith, H.H., Shahinian, P., and Achter, M.R.

6. REPORT DATE March 27, 1967	7a. TOTAL NO. OF PAGES 14	7b. NO. OF REFS 5
8a. CONTRACT OR GRANT NO. NRL Problem M01-09 b. PROJECT NO. RR 007-01-46-5407 c. d.	9a. ORIGINATOR'S REPORT NUMBER(S) NRL Report 6489 9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report)	

10. DISTRIBUTION STATEMENT

Distribution of this document is unlimited.

11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY Department of the Navy (Office of Naval Research), Washington, D.C. 20360

13. ABSTRACT

A new resonance-type flexural fatigue machine has been used to test Inconel X, a low damping capacity material, and Type-316 stainless steel, a high damping material, at 500° and 800°C. A comparison was made of the reproducibility of the data obtained by various test procedures with smooth and notched specimens. Observations were made of the type of cracking in these materials. The progression of cracking appeared to be reflected in resonant frequency changes during the test. The reproducibility of the fatigue data, in particular of the Inconel X, which has a sharp resonance, is sufficiently good to permit distinguishing environmental effects, the main purpose for which the equipment was designed.

DD FORM 1 NOV 65 1473 (PAGE 1)

S/N 0101-807-6801

Security Classification

14. KEY WORDS	LINK A ROLE	LINK A WT	LINK B ROLE	LINK B WT	LINK C ROLE	LINK C WT
Fatigue (mechanics)						
Nickel alloys						
Inconel X						
Steel						
Vacuum apparatus						
Environmental tests						
Test equipment						
Vibrators (mechanical)						
Resonance						
High temperature						