CR 54775

DETERMINATION OF ELEVATED-TEMPERATURE FATIGUE DATA ON REFRACTORY ALLOYS IN ULTRA-HIGH VACUUM

FIFTH QUARTERLY REPORT

Prepared for
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
LEWIS RESEARCH CENTER
UNDER CONTRACT NAS 3-6010

TRW EQUIPMENT LABORATORIES
CLEVELAND, OHIO

NOTICE

Request for copies of this report should be referred to

National Aeronautics and Space Administration
Office of Scientific and Technical Information
Washington 25, D. C.

Attention: AFSS-A

NAS-CR 54775

Fifth Quarterly Report

for

1 July 1965 to 1 October 1965

DETERMINATION OF ELEVATED-TEMPERATURE FATIGUE DATA ON REFRACTORY ALLOYS IN ULTRA-HIGH VACUUM

Prepared by:

C.R. Honeycutt and J.C. Sawyer

Approved by:

E. A. Steigerwald

Prepared for:

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
CONTRACT NO. NAS 3-6010

TECHNICAL MANAGEMENT

Paul E. Moorhead
Space Power Systems Division
NASA - Lewis Research Center

October 15, 1965

TRW EQUIPMENT LABORATORIES
TRW Inc.
23555 Euclid Avenue
Cleveland, Ohio 44117

FOREWORD

The work described herein is being performed by TRW Inc. under the sponsorship of the National Aeronautics and Space Administration under Contract NAS 3-6010. The purpose of this study is to obtain fatigue life data on refractory metal alloys for use in designing space power systems.

The program is administered for TRW Inc. by E. A. Steigerwald, Program Manager, C. R. Honeycutt and J. C. Sawyer are the Principal Investigators.

TABLE OF CONTENTS

		Page No.
I.	INTRODUCTION	1
II.	MATERIALS	1
III.	PROCEDURE	8
IV.	RESULTS AND DISCUSSION	10
	1. Notch Tests	10
	2. Smooth Specimen Tests	15
	3. Comparative Creep and Fatigue Properties	19
V.	FUTURE WORK	19
VI.	BIBLIOGRAPHY	21

I. INTRODUCTION

The purpose of this investigation is to generate fatigue data for refractory alloys at elevated temperatures in ultra-high vacuum environments. The ultimate objective is to determine whether fatigue life or creep is the limiting design parameter in turbine applications involving space-power systems.

During this report period, notched fatigue tests were conducted on TZM alloy in the stress-relieved condition at an ambient temperature of 1800°F (982°C) and on TZC after annealing at 3092°F (1700°C) at an ambient temperature of 2000°F. No well-defined endurance limit was observed in either alloy and fracture occurred in TZC at peak stresses as low as 9,030 psi ($6.22 \times 10^{-9} N/m^2$) in 143 hours ($9.75 \times 10^9$ cycles).

II. MATERIALS

The initial program plan involved testing columbium-base alloy Cb132M and molybdenum-base alloy TZC. The Cb132M, however, could not be forged satisfactorily by the vendor and attempts are currently being made to select an alternate material or material form. The TZC plate material was fabricated according to the two processing cycles shown in Table 1 and the chemical composition of the two heats are shown in Table 2. In addition to the TZC, a TZM alloy in bar form was evaluated and the composition of this material is also given in Table 2.

The TZC material was tested after annealing at 3092°F (1700°C) for 1 hour. This treatment was selected to provide a direct comparison with results of creep tests which are being performed on TZC with a comparable processing history.(1)* The TZM was tested in the as-received condition which consisted of a one hour stress relief treatment at 2250°F (1232°C). The room temperature properties of the test materials are presented in Table 3. In the tensile tests, the TZC specimens were oriented with their tensile axes perpendicular to the rolling direction, while in the TZM samples, the tensile axis was parallel with the axis of the bar stock. This same orientation was maintained during subsequent fatigue tests. The microstructures of the test materials are presented in Figures 1, 2, and 3. The 3092°F (1700°C) annealing treatment produced a recrystallized structure in both heats of TZC material.

* Numbers in parentheses pertain in references in the Bibliography.

TABLE 1

Processing Cycles Used to Fabricate TZC Alloy

I. Processing Cycle No. 1, Heat M-89

a. Vacuum arc melt ingot, 5.88" dia.
b. Machine to 5" dia.
c. Extrude 2.30:1 at 1700°C to 4-1/8" x 2.22" plate,
d. Cut to 4" lengths,
e. Cross-roll at 2925°F (1585°C) in 4" direction to 0.740" using 12" dia. rolls, 4% reduction per pass, hydrogen atmosphere.

II. Processing Cycle No. 2, Heat M-91

Steps a, b, and c same as processing Cycle No. 1
d. Cross-roll on large mill, 28" dia. to produce relatively large degrees of deformation and a finishing temperature of approximately 2372°F (1300°C),
e. Grit blast and cut to final length with abrasive saw.

TABLE 2

Chemical Composition of Alloys Tested

	% Weight				ppm		
	Mo	Zr	Ti	C	H	N	O
TZC Heat M-89	Bal.	0.20	1.45	0.13	5	1	7
TZC Heat M-91	Bal.	0.18	1.25	0.14	1	4	2
TZM Heat 7463	Bal.	0.08	0.48	0.016	-	3	2

TABLE 3

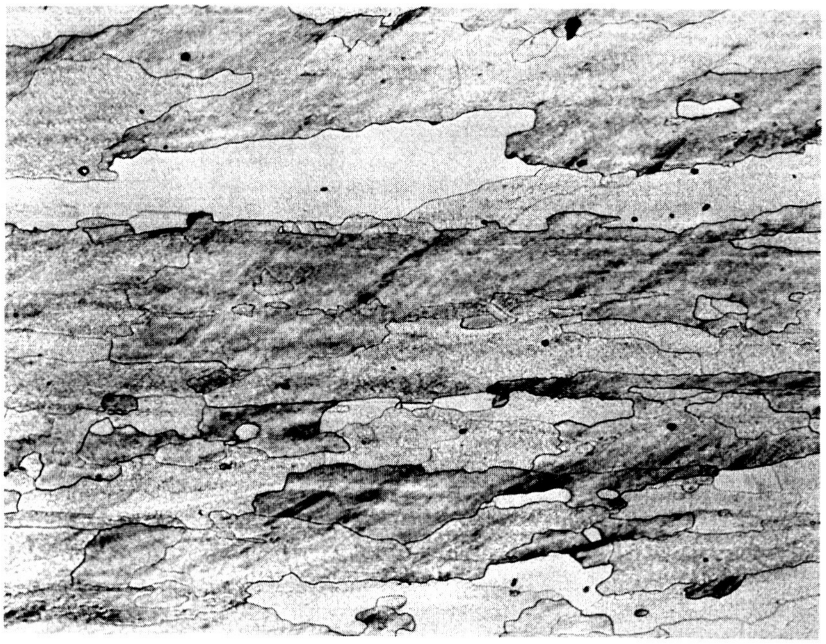
Room Temperature Tensile Properties of TZC and TZM Test Materials

Material	Ultimate Tensile Strength (Ksi, $6.89 \times 10^6 N/m^2$)	0.2% Yield Strength (Ksi, $6.89 \times 10^6 N/m^2$)	Reduction in Area (%)
TZC,* Heat M-80 (same processing as Heat M-89, See Table I) annealed 3092°F (1700°C), 1 Hour.	68.6	68.5	0
TZC, Heat M-91 Annealed 1700°C, 1 Hour,	88.2	47.8	5.6
TZM**, Heat 7463	125.3	112.3	29% Elongation in 4D length

Strain rate 0.005"/"/min.

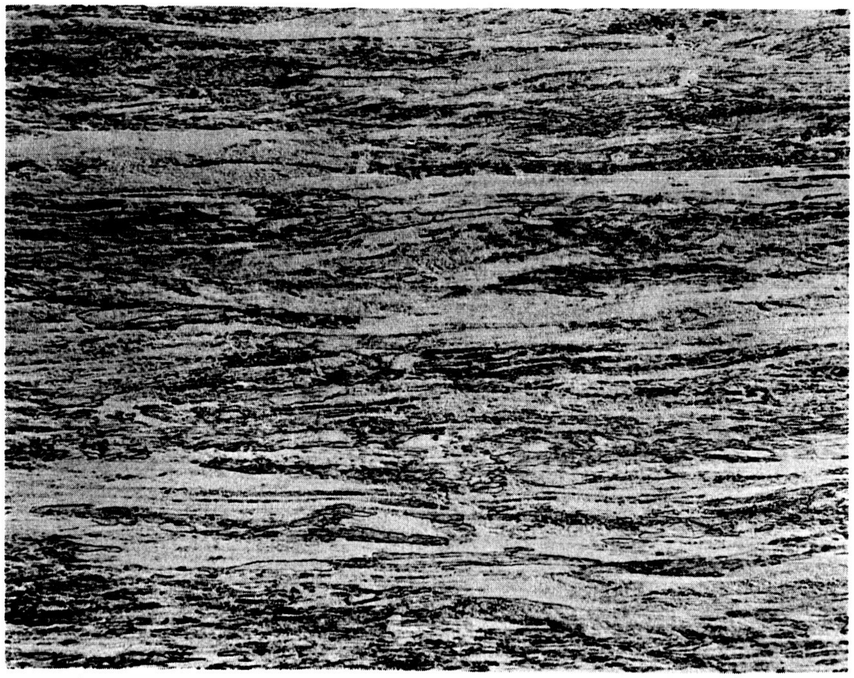
* Specimen failed in a brittle manner so that strength values may not be representative.

** Properties determined by vendor tests.

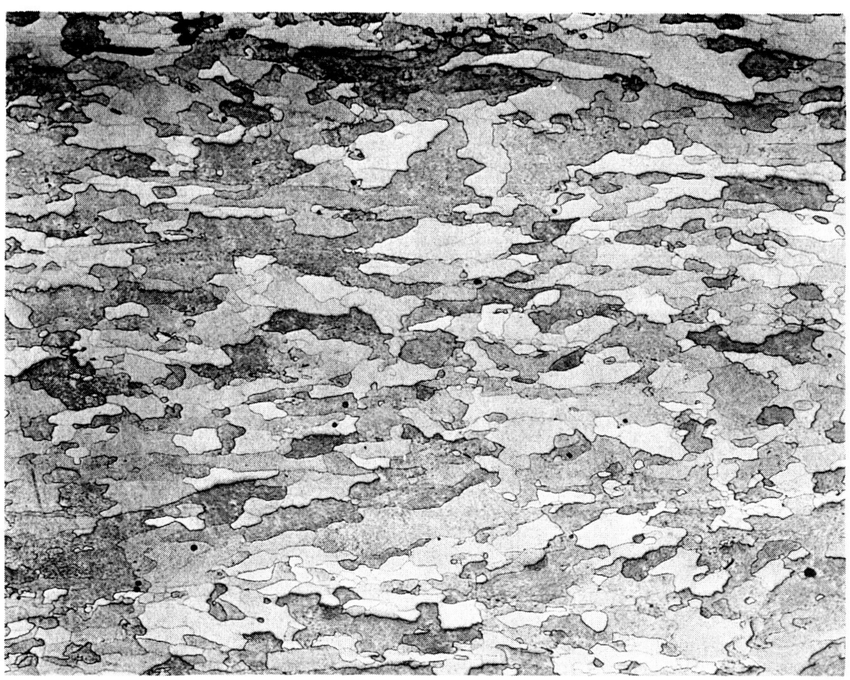


Recrystallized 3092°F
(1700°C), 1 Hour

Figure 1. Microstructure of TZC (Heat M-89), Etchant: 15%HF, 15%H_2SO_4, 8%HNO_3, 62%H_2O, 100X.



As-Received Plate
Cross-Section



Recrystallized 3092°F
(1700°C), 1 Hour

Figure 2. Microstructure of TZC (Heat M-91), Etchant: 15%HF, 15%H_2SO_4, 8%HNO_3, 62%H_2O, 100X.

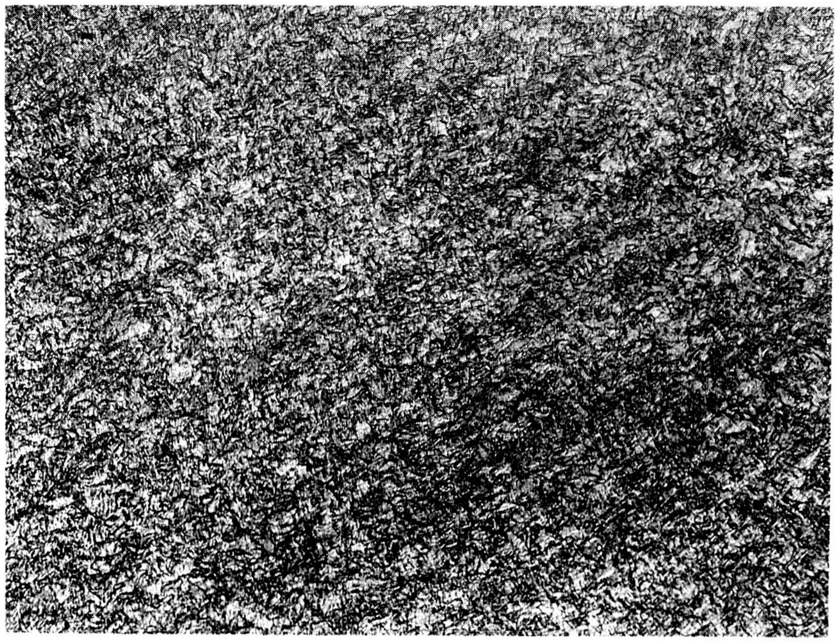


Figure 3. Microstructure of TZM, Bar Stock, Perpendicular to Axis of Bar, Etchant: 15%HF, 15%H_2SO_4, 8%HNO_3, 62%H_2O, 100X.

III. PROCEDURE

The program plan involves fatigue testing the selected alloys as both notch and smooth specimens. Although a 1/8 inch diameter smooth specimen of TZM has been fatigue tested to failure, the major effort during this report period on the unnotched specimen geometry has been devoted to obtaining resonant conditions in the load train which would provide sufficient drive to crack (fatigue) 1/4 inch diameter specimens at temperatures in the 1800 to 2200°F (982 to 1204°C) range. Notch tensile specimens were tested and S-N curves were obtained for TZM and TZC material. The specimen geometry, shown in Figure 4, consisted of 1/4 inch major diameter, a 0.170 inch minor diameter, and a parallel-sided notch with a root radius of 1/32 inch. This geometry represented a theoretical stress concentration factor (K_T) of 1.75 (2). The specimens were tested with an as-machined surface finish which produced an RMS finish of < 15 μ-inch.

The specimen was mounted on the drive train and a W-3%Re/W-25%Re thermocouple was placed approximately 1/8 inch from the surface at the specimen midpoint. Due to breakage produced by the vibration, the thermocouple could not be attached directly to the specimen. The system was pumped to a vacuum less than 10^{-8} Torr, and then the sample was heated to the test temperature at a rate slow enough so that the vacuum never exceeded 1 x 10^{-6} Torr. The temperature was stabilized for approximately two hours and then the cyclic load was applied. The initial tests were conducted with a very slight static tensile load (7.4 Kg) consisting of the weight of the lower half of the specimen and the bracket for mounting the capacitance pick-up gauge.

As a result of the application of the high frequency cyclic load, heating of the fatigue specimen took place. The degree of heating was dependent upon the power applied to the system. In determining the S-N curve, the ambient test temperature; i.e., the temperature recorded by the thermocouple, was set at a fixed value for each test. At the high stress levels where significant heating of the specimen occurred, the test time was sufficiently short so that a readjustment of the furnace temperature to compensate for the self-heating could not be accomplished. At the low values of applied static stress, the temperature increase was very slight and no adjustment of the furnace temperature was usually necessary. Although the data are presented for constant values of the ambient temperature, the actual specimen temperature is also recorded in cases where the test duration was sufficient to allow time for accurate readings. The temperature increase due to self-heating was obtained by measuring the difference in specimen brightness temperature before and after the application of the cyclic load with an L-N optical pyrometer.

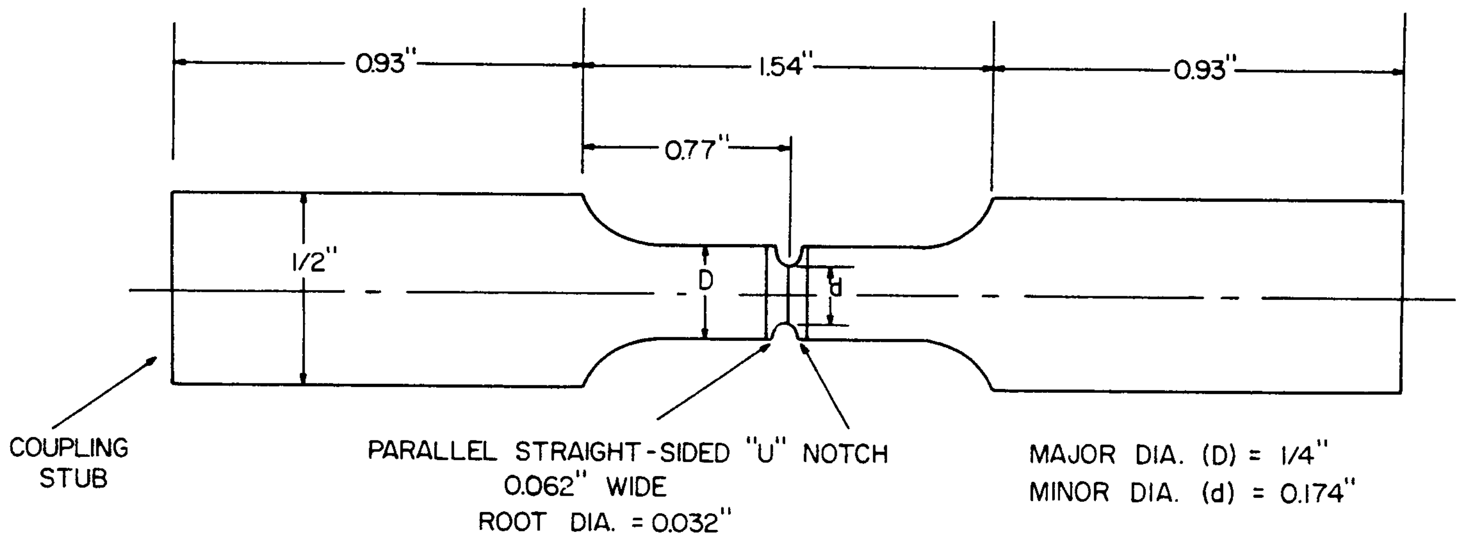


FIG. 4: GEOMETRY OF NOTCH TENSILE SPECIMEN.

The magnitude of the cyclic stress was determined by measuring the displacement of a reference mark on the specimen. Displacement measurements were made at selected positions on the major specimen diameter equidistant from the notch. These displacement values were then used to calculate the strain at the specimen midpoint, assuming that no notch was present. The strain was converted to stress by using the modulus of elasticity at the test temperature. The stress at the base of the notch is higher than that present on the major diameter due to ultrasonic stress amplification produced by the decreased area at the notch root. This amplification factor is equal to the ratio of the area of the major to the minor diameter $(\frac{D}{d})^2$. In addition, an effective stress concentration factor (K_f) based on the notch radius also multiplies the peak stress value (Ref. 3). The method of determining the effective stress concentration factor (K_f) which is less than the theoretical stress concentration factor (K_T) has been described in the previous quarterly report (1). For the notch geometry employed in this program, a K_f value of 1.50 was used.

The accuracy of the stress determinations is not only dependent upon the displacement measurements but is also sensitive to the value of the elastic modulus. Modulus measurements reported in the literature (4,5,6) for both dynamic and static measurements on TZM and unalloyed molybdenum are plotted in Figure 5. The results indicate that there is a significant difference between the dynamic and static modulus measurements. For a given test method, however, the values obtained for unalloyed molybdenum and the TZM alloy were comparable. Although dynamic modulus tests are currently being conducted on the alloys under test in this program, the presently-reported stress values shown in Figure 6 were calculated with moduli obtained by extrapolation of the dynamic test data in Figure 5. A value of 37.5×10^6 psi (2.58×10^{11} N/m^2) was used for the TZM at an ambient test temperature of 1800°F (982°C) and a value of 35.0×10^6 psi (2.4×10^{11} N/m^2) for the TZC data at 2000°F (1093°C).

The fatigue tests were conducted in the 18 to 19 Kcs (kHz) frequency range. When cracking in the test specimen occurred, a significant decrease in resonance frequency was apparent. The end point of the test was defined by this variation in the drive characteristic.

IV. RESULTS AND DISCUSSION

1. Notch Tests

Fatigue tests were conducted on notched specimens (K_T = 1.75) of TZM at 1800°F (982°C) and TZC (Heat M-89) at 2000°F (1093°C). The test data are presented in Tables 4 and 5 and summarized in Figure 6. The stress is plotted as the peak value taking into account the calculated intensification due to the presence of the notch. A compression-tension cycle was employed with a constant static load equal to the weight

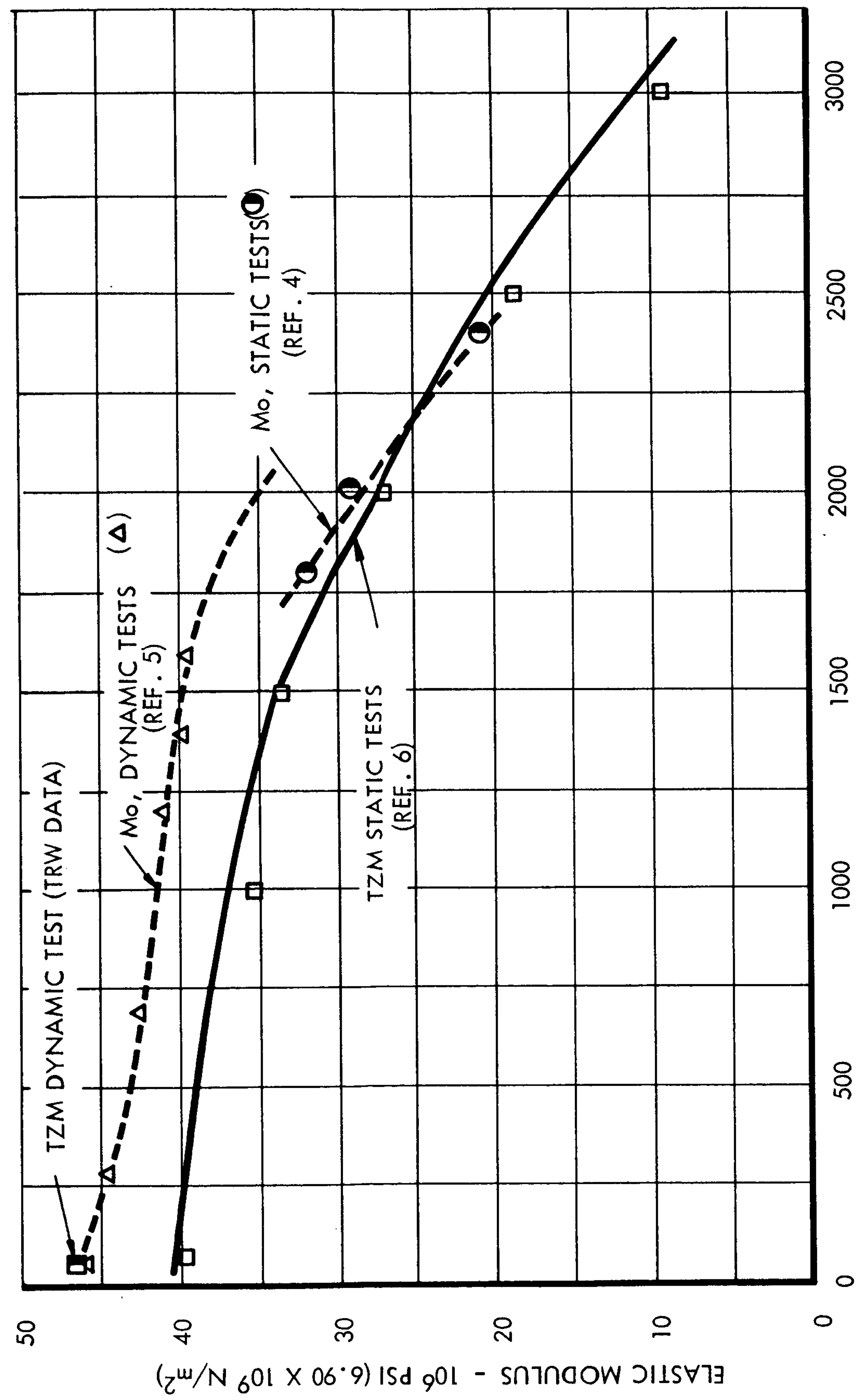


FIGURE 5 VARIATION OF ELASTIC MODULUS WITH TEMPERATURE FOR MOLYBDENUM ALLOYS

TABLE 4

Summary of Data Obtained from Notched Fatigue Tests on TZM Specimens, Stress Relieved Condition
Ambient Test Temperature 1800°F (981°C), Frequency 18.6 Kcs (kHz)

Specimen	(A) Displacement Magnitude (μ-in.)	(B) Displacement Dist. from Center (in)	(C) Strain (in/in)	(D) Stress Based on Smooth Specimen (Ksi, $6.89 \times 10^6 N/m^2$)	(E) Peak Dynamic Stress (Ksi)	(F) Static Notch Stress (Ksi)	(G) Total Peak Stress (Ksi)	(H) Cycles to failure (KHz)	(I) Time to failure (hours)
9AA	55	0.350	157	5.90	18.7	1.02	19.7	8.20×10^6	0.13
10	54	0.355	152	5.70	18.1	1.02	19.1	6.22×10^8	9.3
11	56	0.399	141	5.30	16.8	1.02	17.8	1.61×10^8	2.4
12	43	0.378	114	4.28	13.6	1.02	14.6	1.61×10^{10}	239

Column C: calculated from displacement measurements on major diameter, assuming no notch

Column D: calculated by multiplying strain by elastic modulus, 37.5×10^6 psi

Column E: column D multiplied by K_f=1.50 and ratio of major-to-minor diameter squared $(D/d)^2 = 2.11$

Column F: static average stress (drive train below specimen) multiplied by effective stress concentration factor (K_f=1.50)

Column G: summation of columns E and F.

TABLE 5

Summary of Data Obtained from Notched Fatigue Tests on TZC Specimens, Recrystallized 3092°F (1700°C)
Ambient Test Temperature 2000°F (1093°C), Frequency 19.0 Kcs (kHz)

Specimen	(A) Displacement Magnitude (μ-in)	(B) Displacement Dist. from Center (in)	(C) Strain (in/in)	(D) Stress Based on Smooth Specimen (Ksi, 6.89 x $10^6 N/m^2$)	(E) Peak Dynamic Stress (Ksi)	(F) Static Notch Stress (Ksi)	(G) Total Peak Stress (Ksi)	(H) Cycles to failure (KHz)	(I) Time to failure (hours)	(J) Temperature Increase Due to Drive (°F)	(J) (°C)
2	> 237	0.590	>401	>14.0	> 44.4	1.02	>45.4	8.9 x 10^6	0.08	*	
3	203	0.557	365	12.8	40.6	1.02	41.6	2.06 x 10^7	0.20	*	
4	151	0.511	296	10.4	32.8	1.02	33.8	2.17 x 10^8	3.10	27	15
7	111	0.573	196	6.86	21.7	1.02	22.7	3.77 x 10^8	5.5	*	
9	53	0.551	96.0	3.36	10.6	1.02	11.6	1.81 x 10^9	26.5	*	
12	50	0.523	95.5	3.34	10.5	1.02	11.5	3.01 x 10^9	44.0	28	15
11	42	0.582	72.1	2.53	8.01	1.02	9.03	9.75 x 10^9	143.0	0	0

Column C: calculated from displacement measurements on major diameter, assuming no notch

Column D: calculated by multiplying strain by elastic modulus, 35 x 10^6 psi

Column E: column D multiplied by K_f = 1.50 and ratio of major-to-minor diameter squared $(D/d)^2$ = 2.11

Column F: static average stress (drive train below specimen) multiplied by effective stress concentration factor (K_f = 1.50)

Column G: summation of columns E and F.

* No temperature measurements obtained.

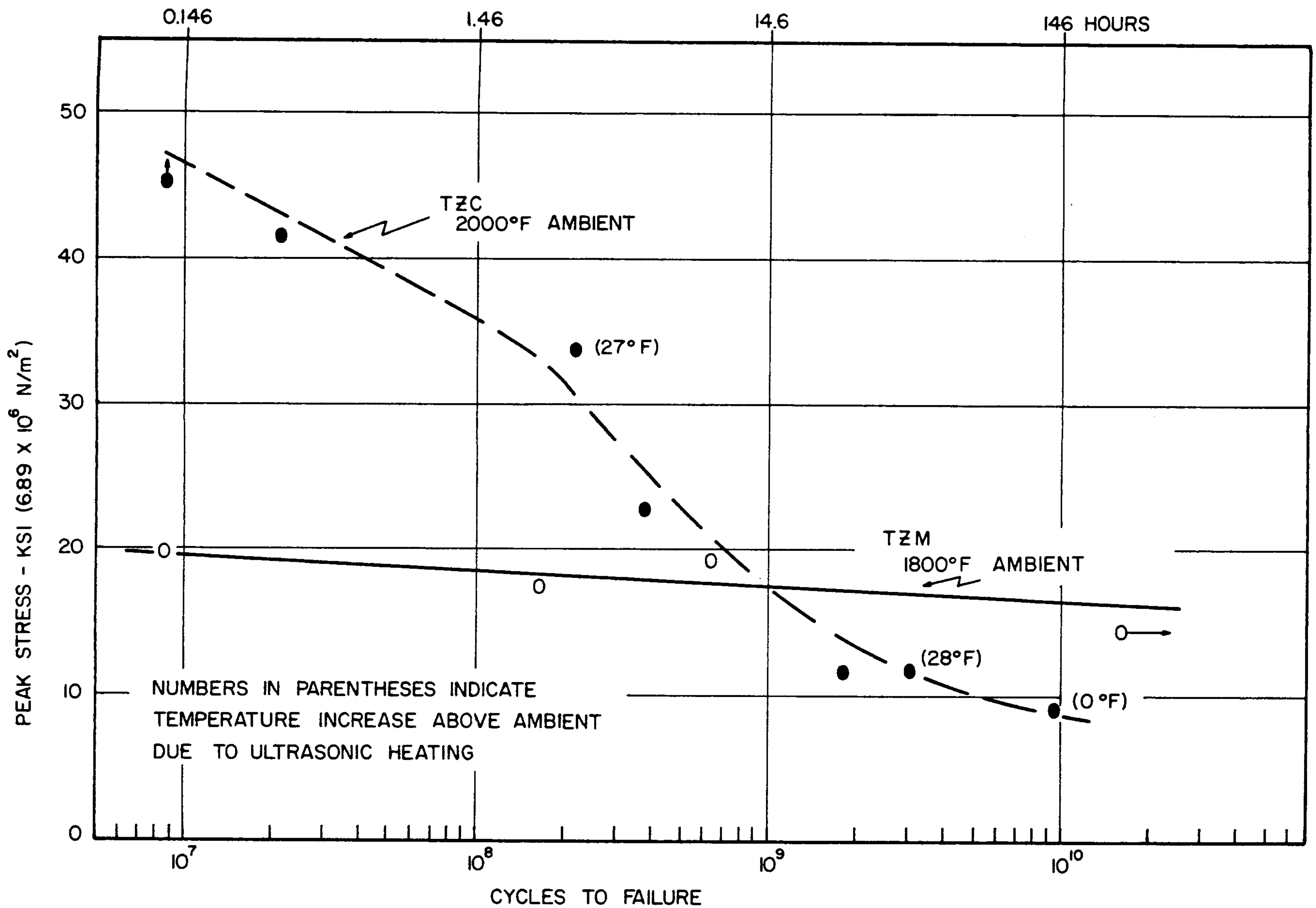


FIG. 6: FATIGUE CURVES FOR TZM (RECRYSTALLIZED AT 3092°F) AND TZM (STRESS-RELIEVED CONDITION) TESTED IN VACUUM ENVIRONMENT $< 10^{-8}$ TORR.

of the lower half of the specimen and the fixture for holding the capacitance pick-up (see Column F in Tables 4 and 5).

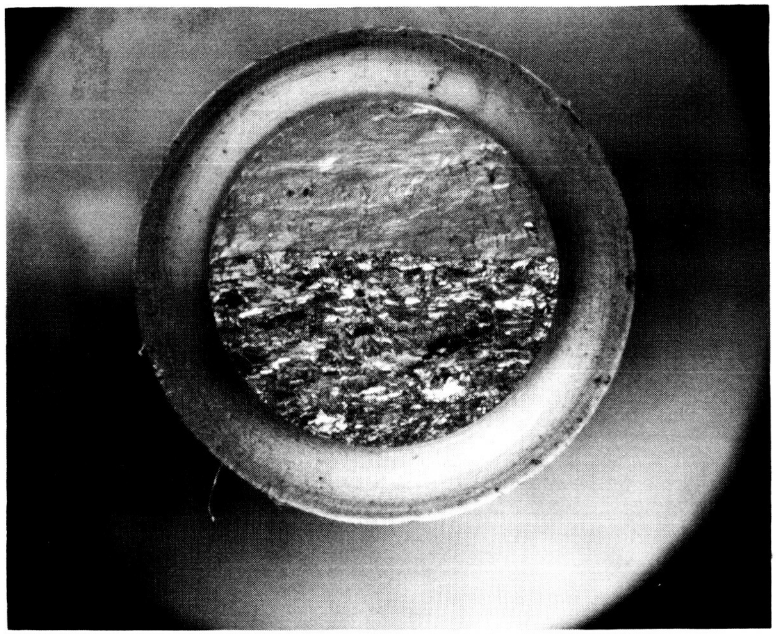
The TZM exhibited a fatigue curve that was extremely sensitive to stress level in the 10^7 to 10^{10} cycle range. By comparison the fatigue strength of the TZC decreased from a calculated stress of 45 ksi ($3.1 \times 10^8 N/m^2$) to less than 10 ksi ($6.89 \times 10^7 N/m^2$) over approximately the same range of test cycles. Neither material showed a true endurance limit at the selected test temperatures.

The appearance of representative fracture surfaces are shown for both the TZC and TZM in Figures 7 and 8. The fracture appearance clearly indicates the region of fatigue crack growth which normally covers approximately one-half of the specimen cross-section. The appearance of "beach marks" is also more apparent in the TZM specimens which were tested in the stress-relieved condition.

The rather steep slope of the S-N curve for the TZC material (see Figure 6) is somewhat unexpected since conventional results generally indicate a very stress sensitive relationship at high cycles similar to that present for TZM. The appearance of the TZC surfaces (see Figure 9) indicates that appreciable surface rippling has occurred at the base of the notch. This effect indicates that localized flow has occurred and suggests that the flow may result in an effective stress concentration factor in the high stress range which is less than that employed to calculate the peak stress values.

2. Smooth Specimen Tests

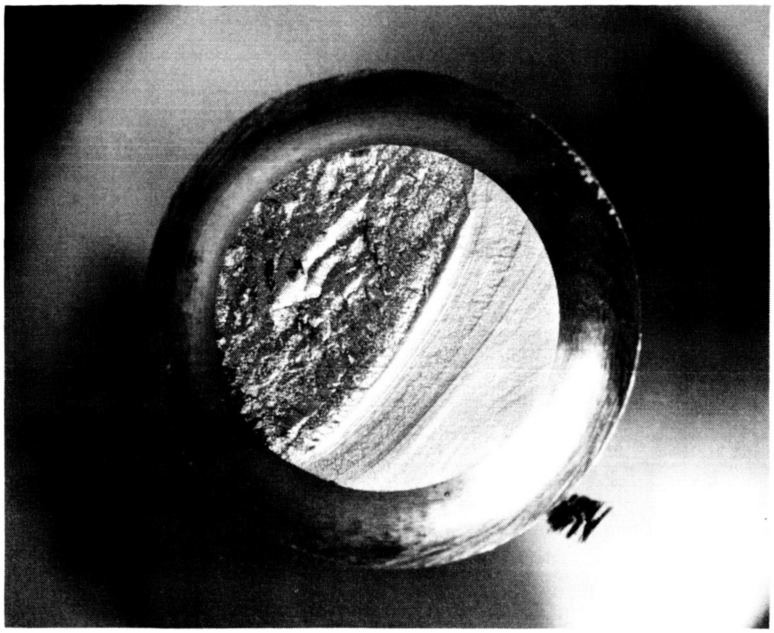
Thus far, the ultrasonic drive system has not produced sufficient cyclic stress to cause fatigue fracture in either a TZC or TZM smooth specimen at test temperatures in the 1800 to 2000°F (981 to 1093°C) range. During this report period, a tension-compression test was conducted on 1/4 inch diameter smooth specimen of TZC (Heat M-89, annealed 3200°F, 1 hour) at a peak stress of 15,000 psi ($1.03 \times 10^8 N/m^2$) for 69 hours (4.8×10^9 cycles) at 2000°F (1093°C) without producing any indication of fracture. At present, no explanation is apparent as to why the notch specimens fractured at a calculated peak stress as low as 9.03 ksi ($6.21 \times 10^7 N/m^2$), while the smooth specimens did not fail at a considerably higher stress. Results obtained by several investigators (7,8) using notch specimens on a variety of alloys indicate reasonably good agreement between S-N curves based on notch specimens under ultrasonic conditions and conventional fatigue test results on smooth specimens. The explanation for the difference does not appear to be in the method of calculating peak stress in the notched specimens since any error in the application of either the ultrasonic amplification factor or the stress concentration factor should tend to decrease the calculated stress value.



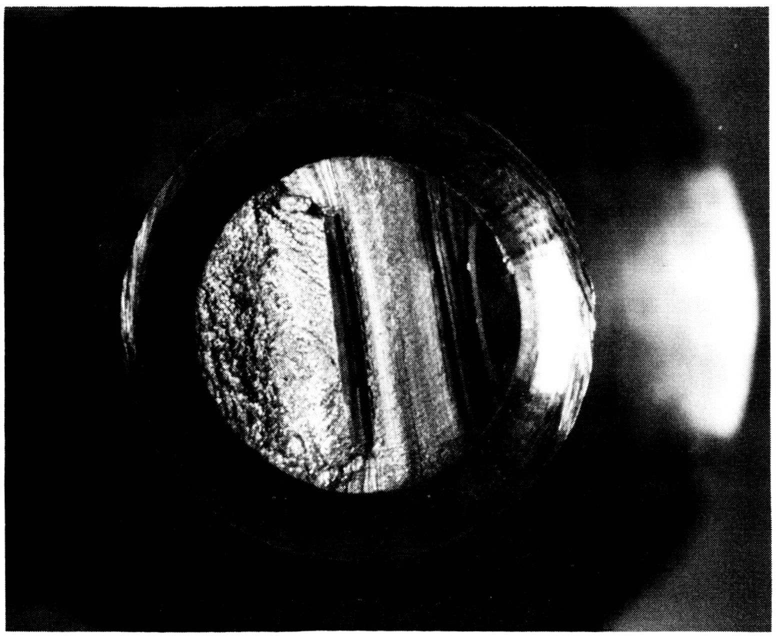
Peak Stress 22.7 Ksi 10X
3.77×10^8 Cycles

Peak Stress 11.6 Ksi 10X
1.81×10^9 Cycles

Figure 7. Fracture Appearance of Notch Fatigue Specimens, TZC (Heat M-89), Annealed 3092°F (1700°C), 1 Hour, Tested at 19.0 Kcs (KHz), 2000°F (1093°C), Vacuum Environment 10^{-8} Torr.

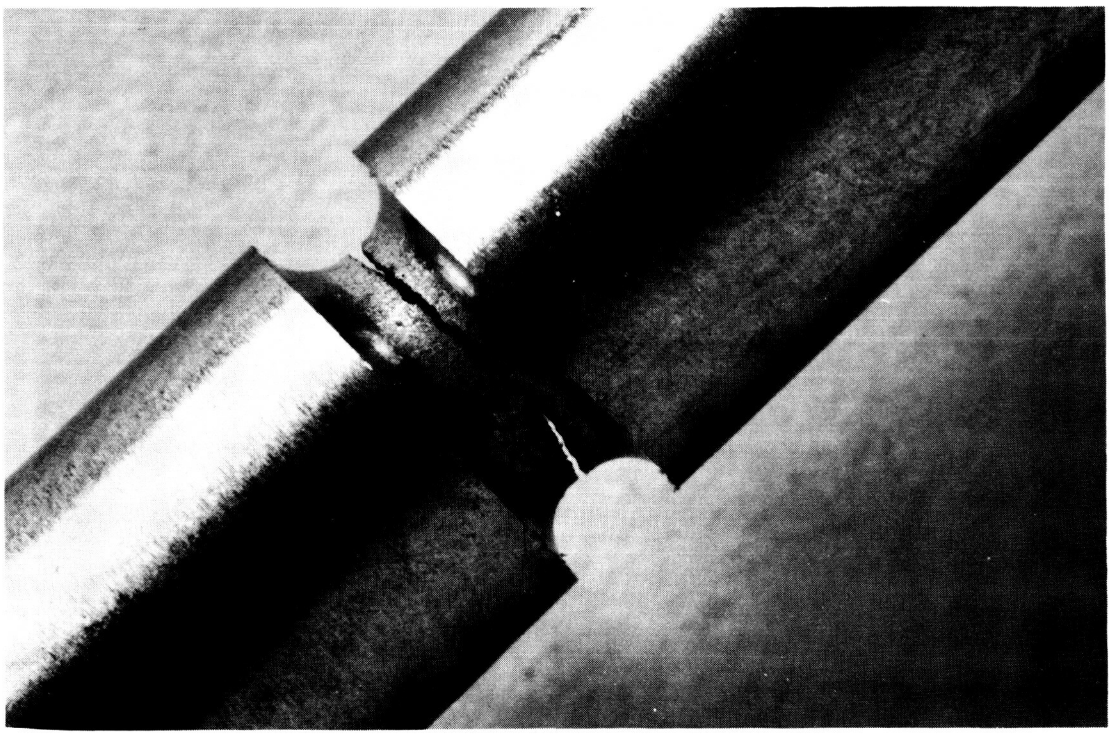


Peak Stress 19.1 Ksi
6.22×10^8 Cycles



Peak Stress 17.8 Ksi
1.61×10^8 Cycles

Figure 8. Fracture Appearance of Notch Fatigue Specimens, TZM, Stress-Relieved Condition, Tested at 18.6 Kcs (KHz), 1800°F (982°C), Vacuum Environment 10^{-8} Torr.



Peak Stress 45.4 Ksi 10X
8.9×10^6 Cycles

Figure 9. Appearance of Specimen Surface in Notch Area Showing Localized Deformation at Notch Root. TZC Annealed 3200°F (1700°C), 1 Hour, Tested at 2000°F (1093°C) Vacuum Environment 10^{-8} Torr.

The attempts to produce increased displacement in the ultrasonic drive system which would enable testing of smooth specimens have been devoted to the following three areas:

(1) Modification of the flange which provides the seal between the piezoelectric drive system and the vacuum chamber.

(2) Improvement of the horn design to allow greater deflections to be obtained, and

(3) Improved tuning of the horn-specimen system at the elevated test temperature.

The use of a thin Viton seal substituted for the weld at the flange, along with the application of hollow horns to the drive train, has increased the displacement in the system by a factor of approximately three. Fracture has been obtained in 1/8 inch diameter smooth specimens of TZM at ambient room temperature. When comparable specimens were heated to 2000°F (1093°C), however, significant loss in displacement occurred as a result of detuning and fatigue failure could not be produced. At present, specimen design is being optimized to provide a resonant system under the test conditions which involve a uniformly-heated specimen and a temperature gradient along the horns which pass through the furnace section.

3. Comparative Creep and Fatigue Properties

Although questions still exist concerning the significance of notch fatigue tests from a design standpoint, it is informative to compare the relative susceptibilities of the test materials for creep and fatigue failure on the basis of the existing results. Figure 10 presents a Larson-Miller plot of 0.5 percent creep data for TZC (1). Superimposed on the creep curve is the fatigue data presented in Figure 6 using the failure times obtained with the loading frequency of 19.0 Kcs (kHz).

Although the fatigue results when presented on a time scale will vary depending on the frequency of load application, the preliminary results, particularly for TZC, indicate that fatigue may be a limiting factor in components operating in a high vacuum environment at high frequencies of load application.

V. FUTURE WORK

Emphasis will be placed on optimizing the design of the loading system so that fatigue failure can be produced in 1/4" diameter test specimens. Additional tests will be performed on notch specimens at varying ratios of dynamic to static load.

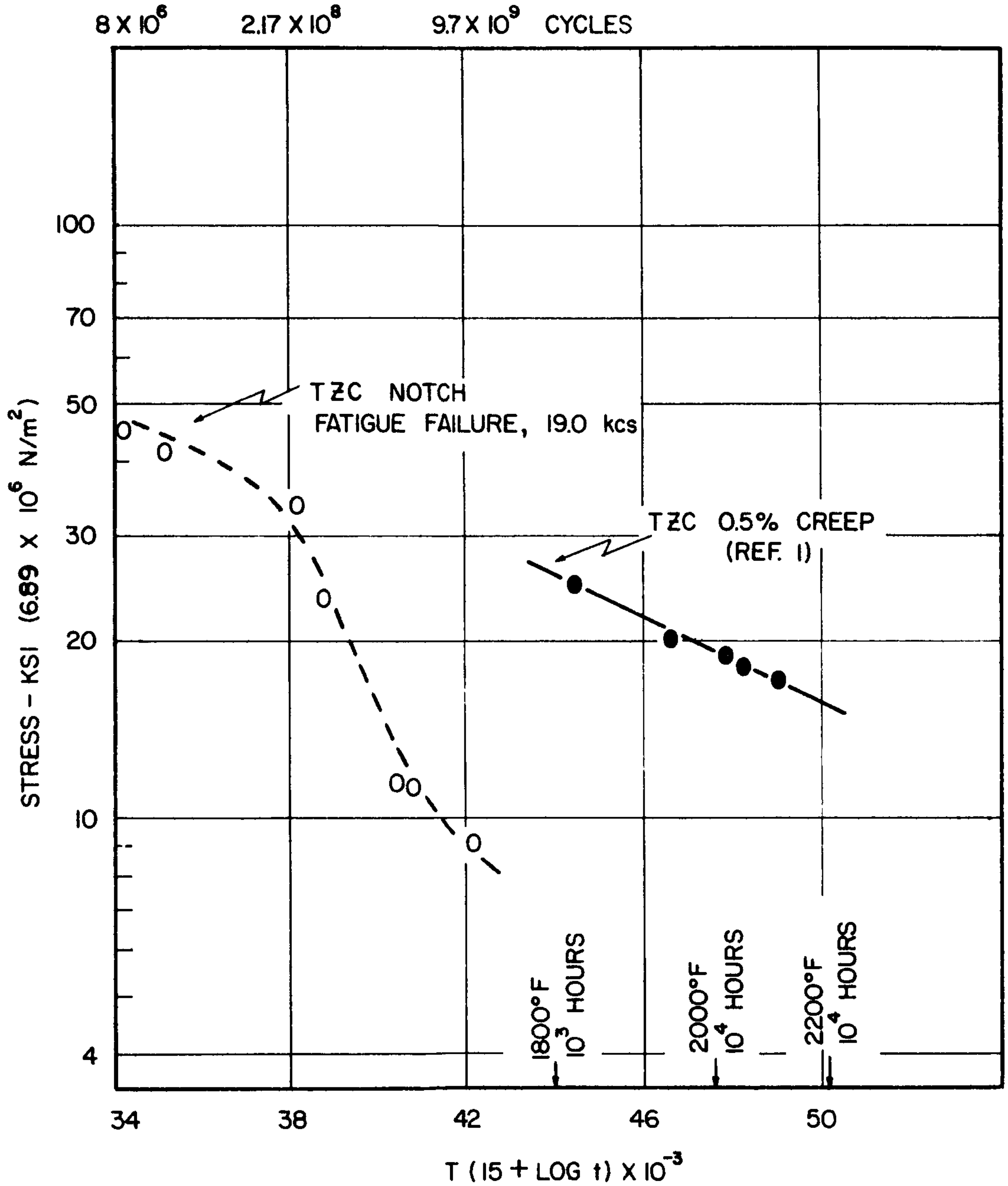


FIG. 10: COMPARISON OF FATIGUE AND CREEP PROPERTIES OF TZC ANNEALED AT 3092°F (1760°C) TESTED IN HIGH VACUUM ENVIRONMENT.

BIBLIOGRAPHY

1. J. C. Sawyer and E. A. Steigerwald, "Generation of Long Time Creep Data on Refractory Alloys at Elevated Temperatures," Ninth Quarterly Report, TRW Inc., NASA Contract NAS 3-2545, (October 1965).

2. R. E. Peterson, "Stress Concentration Design Factors," John Wiley, N.Y., (1953).

3. A. Thiruvengadam, "High Frequency Fatigue of Metals and Their Cavitation Damage Resistance," ONR Contract Nour-3155(00), Tech. Rep. 233-6, (December 1964).

4. R. Q. Barr and M. Semchyshen, "Stress-Strain Curves for Wrought Molybdenum and Three Molybdenum-Base Alloys", Climax Molybdenum Co., (December 1959).

5. Molybdenum Metal, Climax Molybdenum Co., (1960).

6. O. Jones, A. Bennett, and A. J. Albom, "Fabrication Techniques and Mechanical Properties at Elevated Temperatures of TZM Alloy Sheet," The Marquardt Corp., ASD-TDR-62-936, (September 14, 1962).

7. A. Fox, "A Comparison of Ultrasonic and Conventional Axial Fatigue Tests on Aluminum Alloy Rod," Mat. Res. & Stds. 60, (February 1965).

8. A. Thiruvengadam and H. S. Preiser, "Cavitation Damage in Liquid Metals," NASA TPR 467-3, Hydronautics, Inc., NASA Contract NAS 3-4172, (June, 1965).

EXTERNAL DISTRIBUTION

National Aeronautics and Space Administration
Washington, D. C. 20546
Attn: Walter C. Scott
Attn: James J. Lynch (RN)
Attn: George C. Deutsch (RR)

National Aeronautics and Space Administration
Scientific and Technical Information Facility
Box 5700
Bethesda, Maryland 21811 — 2 copies + 2 reproducible

National Aeronautics and Space Administration
Ames Research Center
Moffet Field, California 94035
Attn: Librarian

National Aeronautics and Space Administration
Goddard Space Flight Center
Greenbelt, Maryland 20771
Attn: Librarian

National Aeronautics and Space Administration
Langley Research Center
Hampton, Virginia 23365
Attn: Librarian

National Aeronautics and Space Administration
Manned Spacecraft Center
Houston, Texas 77001
Attn: Librarian

National Aeronautics and Space Administration
George C. Marshall Space Flight Center
Huntsville, Alabama 35812
Attn: Librarian

National Aeronautics and Space Administration
Jet Propulsion Laboratory
4800 Oak Grobe Drive
Pasadena, California 91103
Attn: Librarian

National Aeronautics and Space Administration
21000 Brookpark Road
Cleveland, Ohio 44135
Attn: Librarian
Dr. Bernard Lubarsky (SPSD) MS 86-1
Roger Mather (NPTB)
G. M. Ault MS 105-1
Joe Joyce (NPTB) MS 86-5
Paul Moorhead (NPTB) 10 copies
John E. Dilley (SPSPS) MS 85-1
Norman T. Musial MS 77-1
T. A. Moss (NPTB) MS 86-5
Dr. Louis Rosenblum (MSD) (106-1)
R. Hall MS 105-1
Report Control Center MS 5-5

National Aeronautics and Space Administration
Western Operations Office
150 Pico Boulevard
Santa Monica, California 90406
Attn: Mr. John Keeler

National Bureau of Standards
Washington 25, D. C.
Attn: Librarian

Aeronautical Systems Division
Wright-Patterson Air Force Base, Ohio
Attn: Charles Armbruster (ASRPP-10)
T. Cooper
Librarian
John L. Morris
H. J. Middendorp ASNRG 33143

Army Ordnance Frankford Arsenal
Bridesburg Station
Philadelphia 37, Pennsylvania
Attn: Librarian

Bureau of Ships
Department of the Navy
Washington 25, D. C.
Attn: Librarian

U. S. Atomic Energy Commission
P. O. Box 1102
East Hartford, Connecticut
Attn: C. E. McColley
CANEL Project Office

U. S. Atomic Energy Commission
Germantown, Maryland
Attn: Col. E. L. Douthett
SNAP 50/SPUR Project Office
Attn: H. Rochen
SNAP 50/SPUR Project Office
Attn: Socrates Christofer
Attn: Major Gordon Dicker
SNAP 50/SPUR Project Office

U. S. Atomic Energy Commission
Technical Information Service Extension
P. O. Box 62
Oak Ridge, Tennessee — 3 copies

U. S. Atomic Energy Commission
Washington 25, D. C.
Attn: M. J. Whitman

Argonne National Laboratory
9700 South Cross Avenue
Argonne, Illinois
Attn: Librarian

Brookhaven National Laboratory
Upton Long Island, New York
Attn: Librarian

Oak Ridge National Laboratory
Oak Ridge, Tennessee
Attn: W. C. Thurber
Attn: Dr. A. J. Miller
Attn: Librarian

Office of Naval Research
Power Division
Washington 25, D. C.
Attn: Librarian

Bureau of Weapons
Research and Engineering
Material Division
Washington 25, D. C.
Attn: Librarian

U. S. Naval Research Laboratory
Washington 25, D. C.
Attn: Librarian

Advanced Technology Laboratories
Division of American Standard
369 Whisman Road
Mountain View, California
Attn: Librarian

Aerojet General Nucleonics
P. O. Box 77
San Ramon, California
Attn: Librarian

AiResearch Manufacturing Company
Sky Harbor Airport
402 South 36th Street
Phoenix, Arizona
Attn: Librarian
E. A. Kovacevich

AiResearch Manufacturing Company
9851-9951 Sepulveda Boulevard
Los Angeles 45, California
Attn: Librarian

I. I. T. Research Institute
10 W. 35th Street
Chicago, Illinois 60616
Attn: Librarian

Atomics International
8900 DeSoto Avenue
Canoga Park, California
Attn: Librarian

AVCO
Research and Advanced Development Department
201 Lowell Street
Wilmington, Massachusetts
Attn: Librarian

Babcock and Wilcox Company
Research Center
Alliance, Ohio
Attn: Librarian

Electro-Optical Systems, Incorporated
Advanced Power Systems Division
Pasadena, California
Attn: Librarian

Fansteel Metallurgical Corporation
North Chicago, Illinois
Attn: Librarian
Att: Henry L. Kohn

Philco Corporation
Aeronutronics
Newport Beach, California
Attn: Librarian

General Atomic
John Jay Hopkins Laboratory
P. O. Box 608
San Diego 12, California
Attn: Librarian

General Electric Company
Flight Propulsion Laboratory Dept.
Cincinnati, Ohio 45215
Attn: Librarian

General Electric Company
Missile and Space Vehicle Dept.
3198 Chestnut Street
Philadelphia 4, Pennsylvania
Attn: Librarian

General Electric Company
Missile and Space Division
Cincinnati, Ohio
Attn: J. W. Sennel — 2 copies

General Electric Company
NMPO
Cincinnati, Ohio 45215
Attn: Librarian

General Electric Company
Vallecitos Atomic Laboratory
Pleasanton, California
Attn: Librarian

General Electric Company
Evendale, Ohio 45215
FPD Technical Information Center
Bldg. 100, Mail Drop F-22

General Dynamics/Fort Worth
P. O. Box 748
Fort Worth, Texas
Attn: Librarian

General Motors Corporation
Allison Division
Indianapolis 6, Indiana
Attn: Librarian

Hamilton Standard
Division of United Aircraft Corporation
Windsor Locks, Connecticut
Attn: Librarian

Hughes Aircraft Company
Engineering Division
Culver City, California
Attn: Librarian

Lockheed Missiles and Space Division
Lockheed Aircraft Corporation
Sunnyvale, California
Attn: Librarian

Marquardt Aircraft Company
P. O. Box 2013
Van Nuys, California
Attn: Librarian

The Martin Company
Baltimore 3, Maryland
Attn: Librarian

The Martin Company
Nuclear Division
P. O. Box 5042
Baltimore 20, Maryland
Attn: Librarian

Martin Marietta Corporation
Metals Technology Laboratory
Wheeling, Illinois

Materials Research Corporation
Orangeburg, New York
Attn: Librarian

McDonnell Aircraft
St. Louis, Missouri
Attn: Librarian

MSA Research Corporation
Callery, Pennsylvania
Attn: Librarian

National Research Corporation
70 Memorial Drive
Cambridge 42, Massachusetts
Attn: Librarian

North American Aviation
Los Angeles Division
Los Angeles 9, California
Attn: Librarian

Northrop Norair
3901 West Broadway
Hawthorne, California
Attn: Librarian

Pratt & Whitney Aircraft
400 Main Street
East Hartford 8, Connecticut
Attn: Librarian

Ryan Aeronautical Company
San Diego, California
Attn: Librarian

Republic Aviation Corporation
Farmingdale, Long Island, New York
Attn: Librarian

Solar
2200 Pacific Highway
San Diego 12, California
Attn: Librarian

Southwest Research Institute
8500 Culebra Road
San Antonio 6, Texas
Attn: Librarian

Matthew King
TRW Systems, Inc.
1 Space Park
Redondo Beach, California
Attn: Nuclear Technology

Dr. James Hadley
Head, Reactor Division
Lawrence Radiation Laboratory
Livermore, California

Rocketdyne
Canoga Park, California
Attn: Librarian

Superior Tube Company
Norristown, Pennsylvania
Attn: Mr. A. Bound

Sylvania Electric Products, Inc.
Chemical and Metallurgical
Towanda, Pennsylvania
Attn: Librarian

Temescal Metallurgical
Berkeley, California
Attn: Librarian

Union Carbide Stellite Corporation
Kokomo, Indiana
Attn: Librarian

Union Carbide Nuclear Company
P. O. Box X
Oak Ridge, Tennessee
Attn: X-10 Laboratory Records Department 2 copies

United Nuclear Corporation
5 New Street
White Plains, New York
Attn: Librarian

Universal Cyclops Steel Corporation
Refractomet Division
Bridgeville, Pennsylvania
Attn: C. P. Mueller

Vought Astronautics
P. O. Box 5907
Dallas 22, Texas
Attn: Librarian

Wah Chang Corporation
Albany, Oregon
Attn: Librarian

Westinghouse Electric Corporation
Astronuclear Laboratory
P. O. Box 10864
Pittsburgh, Pennsylvania 15236
Attn: R. Begley

Westinghouse Electric Corporation
Materials Manufacturing Division
RD No. 2 Box 25
Blairsville, Pennsylvania
Attn: Librarian

Westinghouse Electric Corporation
Westinghouse Research Center
Monroeville, Pennsylvania
Attn: Librarian

Wolverine Tube Division
Calumet and Hecla, Inc.
17200 Southfield Road
Allen Park, Michigan
Attn: Mr. Eugene F. Hill

Wyman-Gordon Company
North Grafton, Massachusetts
Attn: Librarian

H. S. Preiser
Hydronautics, Inc.
Pindell School Road
Laurel, Maryland, 20810