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BIMONTHLY PROGRESS REPORT NO. V

THERMAL-SHOCK INVESTIGATION

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OBJECT

The object of this research is to evaluate optimum design of test specimens and criteria which will permit correlation of thermal-shock data with performance of the material in the form of turbine buckets.

SUMMARY

Tests were run to:

a) observe effect of specimen temperature on

   i) number of thermal-shock cycles to failure, and
   ii) scatter of experimental results,

b) observe effect of prior application of alternating stress on number of thermal-shock cycles to failure, and

c) check variations in setup variables.

A tentative procedure has been devised for possible correlation of thermal-shock results on different specimens.

Visits were made to four groups of persons interested in thermal-shock tests.

INTRODUCTION

The previous progress report indicated that reproducibility of test results might be a function of the severity of the thermal-shock cycle, with best reproducibility at greatest severity. This period of research was consequently spent primarily in:

a) altering the experimental rig so that lower air temperatures may be used in future tests,

b) determining the change in severity occasioned by changing specimen temperature, and

c) checking out the altered setup.

The period of research covered is from December 11, 1951, to February 11, 1952.

APPARATUS

The previous apparatus was altered by rotating the air-storage tanks to a horizontal position in order to:

a) increase mixing of incoming air and air in the storage tank,

b) reduce pipe friction, and

c) permit installation of suitable cooling coils.

A two-dimensional nozzle with replaceable throat was constructed and adjusted in order to determine how best to obtain reproducibility in construction of duplicate nozzles.

A sound-minimizing shelter was constructed around the test rig to reduce noise from the air jet.

The second thermal-shock installation was completed. A by-pass runs between the two air tanks to increase plenum capacity.

A total-radiation pyrometer has been procured and will be placed in use shortly.

VISITS

Visits were made to the General Electric Company at West Lynn, Massachusetts; the Pratt and Whitney Aircraft Division at East Hartford, Connecticut; the General Electric Company at Lockland, Ohio; and the National Advisory Committee for Aeronautics at Cleveland, Ohio, for the purpose of exchanging thoughts on thermal-shock research. The results of these visits that were of most immediate interest were:

(1) At the West Lynn plant, some results of tests showed good correlation between impact strength and thermal-shock resistance.

(2) At the East Hartford plant, failures in turbine buckets were seen that were apparently caused by mechanical instability of the bucket, due, at least in part, to unequal temperature distribution.

(3) At the Lockland plant, a turbine bucket was seen that showed small regularly-spaced cracks on the leading edge. This bucket appears to present the most clear-cut evidence yet seen of the presence of thermal cracks in turbine buckets.

(4) At the N.A.C.A. laboratory, references were available to German works that indicated a correlation between impact strength and time of loading under static stress at elevated temperature (reference 1).

The general line of thought on this project appears to be in reasonable agreement with opinions given at the places visited.

ANALYSIS

General Problem

Three problems that appear to be among the most difficult to attack by theoretical means have been under investigation for some time on this project. They are:

(1) What parameters based on material properties govern thermal cracking? How are these parameters (and properties) dependent on temperature? What are the local stresses and temperatures in the specimen?

(2) What is the variation in resistance to thermal-cracking due to differences in specimen shape and size? What is the variation due to testing in different rigs, by different observers?

(3) How can test conditions in the actual gas turbine be described in a simple manner? What are the conditions of stress and temperature in a turbine? Can these conditions be correlated with the "artificial" conditions in a thermal-shock test?

Concept of Deterioration or Damage

With the dawning of the realization that fairly exact answers to the above questions would be difficult or impractical to obtain by direct theoretical means, a new line of reasoning was set up in an attempt to obtain answers by side-stepping the major difficulties without ignoring their existence. What is hoped is a start on a practical answer to these questions is tentatively set forth in admittedly oversimplified fashion below.

It can be shown that no reasonable conditions of temperature distribution and restraint of specimen can cause cracking in the usual materials employed for gas-turbine blading because the strains set up by the temperature gradients cannot exceed the fracture strains (or strains at which necking begins) of the materials as determined by tensile tests. Exceptions to this statement can be found for the cases where:

a) the tensile load is applied so rapidly that the strain at fracture is much less than for conventional static tests,

b) a very high stress-concentration exists, as at the ends of cracks, and

c) the specimen contains highly unequal cross sections.

These exceptions can be set aside for the following reasons:

a) Qualitative observations of rates of cooling of thermal-shock specimens in this project show that the rate of cooling appears to be less than that required to diminish the usual value of strain at fracture materially.

b) The quality of turbine buckets is such that no cracks (at least of any great depth) are present in the new turbine bucket.

c) The shape of turbine buckets is such that no large changes of cross section are present in the usual zone of failure.

The question was raised at all visits as to whether anyone had ever observed a thermal (or quenching) crack in a material of reasonable ductility (say 10% elongation in 2 inches for a test bar of 1/2-inch diameter). Materials which transform during the shock (or quench) to types definitely known to possess very low ductility were excepted, as were specimens of very rapidly changing cross section. The replies indicated that no such cracking had been positively observed.

The almost inescapable conclusion is that turbine-bucket materials crack during thermal-shock tests because the stress and/or temperature history has altered the original material so that it no longer possesses the same ductility at fracture, and probably has altered other structure-sensitive properties also.

Evaluation of Damage

It seems reasonable to assume that certain material parameters govern thermal cracking and that these parameters are dependent on temperature. If these parameters, however, are dependent on the past history of stress and temperature experienced by the specimen, it becomes necessary to evaluate the effect of this history on the properties of the materials under study. It is not necessary to speculate on the local mechanism by which the deterioration has occurred if one is interested only in a measure of the deterioration.

A first thought on possible evaluation of such properties as tensile strength and ductility might be that specimens could be run in the shock rig for a while and then tested in tension or in impact. The decrease in tensile strength, ductility, or impact strength would be a measure of the damage done to the specimen during the thermal-shock history. The use of the impact test to evaluate deterioration is not new: reference 1 shows the effect of stress-rupture loading on impact strength; also, many investigators have worked with damage-line testing in fatigue.

But the question arises as to how to improve the sensitivity of any process for evaluation of damage or deterioration.

There is no reason to expect that the change in properties is the same throughout the entire specimen. Thus, an attempt to detect such changes as altered ductility might well be predestined to failure if only a small volume of material had become brittle. A more effective test would be one that is more sensitive to the changes in small volumes of material. If the deterioration (as seems reasonable) is greatest on the outer surface of the specimen, a suitable test for deterioration should be such as to emphasize the properties of the surface material.

Tests such as rotating-beam fatigue and thermal-shock itself might be suitable tests, since each emphasizes properties at the outer surface. An alternative procedure would be to cut smaller specimens for tensile testing from the original thermal-shock specimen. It is desirable to avoid additional specimen preparation, so the idea of cutting smaller specimens will be discarded, at least for the present.

From another point of view, it can be assumed that thermal-shock failure is primarily a function of two simple failure mechanisms, namely, stress-rupture loading and fatigue loading. That is, a given thermal-shock history may be envisioned to proceed from a combination of fatigue cycles (equal in number to the number of thermal-shock cycles) and a simultaneous application of stress-rupture loading. A somewhat naive statement of the criterion of failure could be that for given thermal stress and temperature, the amplitude of fatigue stress at other than a zero mean stress controls failure. But the very conditions of stress and temperature are functions of properties such as thermal conductivity, specimen size, speed of air blast, and so forth. Thus, this alternative point of view is too complicated to provide the complete answer concerning a thermal-shock parameter, but it serves the purpose of indicating that rotating-beam fatigue and stress-rupture are suitable for <u>causing</u> deterioration as well as measuring prior deterioration. For example, the deterioration due to thermal shock can be set equivalent to a certain amount of deterioration due to fatigue, the equivalence meaning that the number of thermal-shock cycles to failure is the same for previous thermal-shock deterioration as for previous fatigue deterioration. Thus, fatigue (for example) can be used to damage a material, after which it is placed in a thermal-shock test to determine the change in number of thermal-shock cycles to failure; <u>or</u> thermal shock can be used to damage a specimen (short of cracking), after which the change in the number of fatigue cycles to failure may be determined.

The damage done to the specimen in thermal-shock test prior to cracking is a consequence of its individual history of stress and temperature. The importance of evaluation of this history lies partly in the fact that the properties of the material itself--thermal expansivity, stress-strain relations, cold working properties, and so forth--serve to determine this history. These properties vary from material to material and consequently the difference in history between 2 specimens in a thermal-shock rig may not be the same as the difference in the respective histories in the turbine. It is necessary then, to evaluate this artificial history.

This line of reasoning leads to the following tentatively proposed technique for describing the history placed on a specimen during the thermal-shock test. The specimen is subjected to a given number of fatigue cycles at a given maximum stress (or a given stress-rupture loading for a given time, or some combination of the two). It is then evaluated in thermal shock. This procedure is repeated either with different stresses, different numbers of fatigue cycles, or different times of stress-rupture loading. The drop in number of thermal-shock cycles until failure would be set equivalent to fatigue deterioration for the number of cycles at the stress given (or other damage-producing effect).

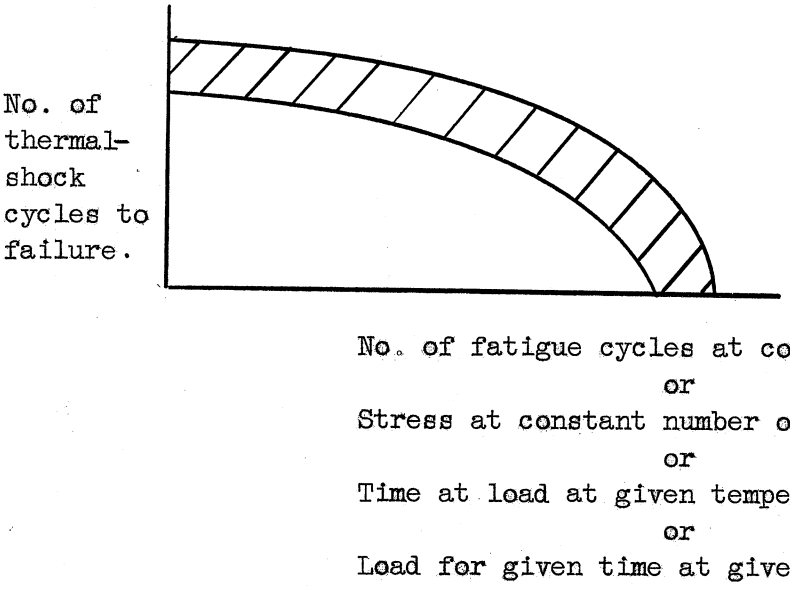


Fig. 1.
Hypothetical graph of measurements of thermal-shock damage.

The stress-rupture type of deterioration has been evaluated by impact tests in reference 1 as already noted. It should be mentioned that the reference showed some materials were more resistant to rapid deterioration than others, and that some deterioration could be removed by subsequent heating. These factors may alter the shape of the above curve for different materials.

Application to General Problem

(1) What parameters based on material properties govern thermal cracking? How are these parameters (and properties) dependent on temperature? What are the local stresses and temperatures in the specimen?

The analysis just given may be used to determine a procedure, not for answering the above questions, but for obtaining the ultimate results towards which these questions were leading.

Let the steady-state temperature and stress-rupture loading in the failure zone be determined for the particular turbine under consideration (experimentally, or by calculation based on experience). These values will vary for different turbine-bucket materials and conditions of operation. Determine deterioration at that stress-rupture condition for various times of loading by using thermal-shock as a criterion of damage. A scatter band as in Fig. 1 may be expected to result.

A proposed parameter might then be: number of thermal-shock cycles to failure after a known prior history simulating turbine history has been imposed on the specimen.

(2) What is the variation in resistance to thermal cracking due to differences in specimen shape and size and differences in test rigs? A suitable method of evaluating the history given by the thermal-shock test may be to determine the equivalence of history in the different specimens in terms of a determinable quantity such as fatigue damage. Each type of specimen or rig would be used in thermal shock after several pairs of identical fatigue histories had been placed in the respective specimens. The decrease in the number of thermal-shock cycles for given identical histories would measure the relative histories of the two specimens.

It is known that differences in fatigue life exist due to variation of specimen size and shape, but the differences are small if the specimens are not too small in depth of cross section (say, below 1/4 inch in depth) and if stress concentration factors are minor. Stress-rupture loading could be used similarly.

(3) How can conditions in the gas turbine be taken into account? The problem here is now identical with the problem in (1), and has been answered.

Conclusions

It is hoped that the concept of deterioration may be used in evaluating the:

(1) equivalence of the history placed on the shock specimen by thermal shock and an easily reproducible history such as fatigue and/or stress-rupture history,

(2) equivalence of specimens of different shapes and sizes, tested in different rigs, and

(3) equivalence of thermal-shock test conditions and turbine conditions.

EXPERIMENTAL RESULTS

The check tests on the altered thermal-shock rig indicate that thermal-shock failures are occurring at approximately the same numbers of cycles as previously, or somewhat fewer.

S-816 alloy specimens were tested at maximum cycle temperatures of 1700, 1600, and 1500°F. There is a fairly significant trend to indicate that decreasing the specimen temperature decreased the severity of shock or the susceptibility of the specimen to failure, since the number of cycles required for failure was increased. It is too early to discuss reproducibility at the different temperatures, but very tentatively, the scatter of results increased as specimen temperature was decreased. It is not obvious that variation of cycles to failure should necessarily have been as shown.

The type 347 stainless-steel specimens that were tested after having been subjected to fatigue loading showed, on the average, reduced numbers of thermal-shock cycles to failure. It is too early to hypothesize on the shape of a curve relating fatigue cycles to thermal-shock cycles for failure.

SUMMARY OF RESULTS

1. Thermal cracking required more thermal-shock cycles for S-816 alloy as temperature was lowered from 1700 to 1500°F.

2. Prior fatigue damage short of failure appeared to reduce the number of thermal-shock cycles to produce cracking in type 347 stainless steel.

3. A concept of damage has been developed for possible correlation of results from different specimens and test-rigs. The equivalence of results may be expressed in terms of known prior damage. This correlation may be suitable for comparing results in turbines and in the shock rig.

REFERENCE

1. Versprödung und Schädigung warmfesten Stähle bei Dauerstandbeanspruchung by A. Thum and K. Richard. *Arch. für das Eisenhüttenwesen,* *15*, No. 1, 33-45 (July, 1941).

KEY TO LOG

Column (2)

	Arrow indicates direction and location of cooling jet; cooling medium is air unless otherwise stated
W	Cooling medium is water
.045	Width of cooled edge, inch
P.F.	Previously subjected to rotating-beam fatigue as shown in column (6)
X	Failed during pre-fatigue

Column (3)

M	Thermal-shock cycle manually controlled
1500/5	Automatic cycle control; maximum temperature, °F, and length of cooling period, seconds
P1800	Dead load, 1800 lbs
+10/100	Starting with stated maximum temperature, maximum temperature was increased 10°F after each 100 cycles
40.5K	Reversed-bending (rotating-beam) fatigue tests; maximum stress, 40,500 psi
to 1800	Maximum temperature held constant after 1800°F was reached

Column (4)

A	Air cooling for stated number of cycles
W	Water cooling for stated number of cycles
no symbol	Air cooling for stated number of cycles

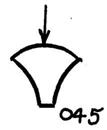
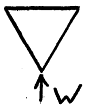
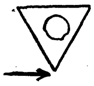
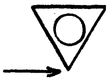
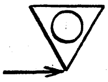
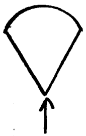
Column (5)

O	No failure visible
F	Fracture
C	Cracks
G	Grooves

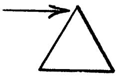
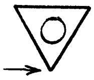
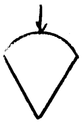
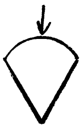
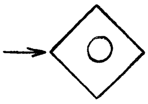
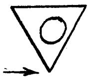
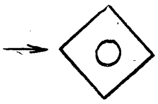
Column (6)

B	Specimen warped due to thermal strains
A0.14	Area of cross section, square inch
T300/1600	Heat treated before testing 300 hr at 1600°F
G1500	Grooves first appeared at 1500 cycles
OH	Stated maximum temperature was exceeded due to malfunction of control unit
BT	Broke through to thermocouple hole
40.5K 82000	Previously subjected to 82,000 cycles at 40,500 psi
R	Reproducibility test
N	Specimen formed a neck
+100/5108	Temperature increased 100°F at 5108 cycles
Check II	Second test run to check operation of test rig after alteration

TEST LOG

Specimen Number (1)	Cross Section (2)	Cycle (3)	Number of Cycles (4)	Type of Failure (5)	Remarks (6)
Type 304 Stainless Steel					
1		M	______	O	B
2		1600/10	4400 A 300 W	C	B
3		1600/4 +10/100	1783	C	
4a 4b	Fatigue Specimens	40.5K 40.5K	3300 2600	F F	
5		1700/4 1800/4	1100 675	O C	
6		1600/4 1900/4	6240 1240	O C	G6500
7		1500/5 P600	4130	F	A 0.16
8		1600/5 1800/4	3082 517	O C	T300/1600

TEST LOG (cont)

Specimen Number (1)	Cross Section (2)	Cycle (3)	Number of Cycles (4)	Type of Failure (5)	Remarks (6)
9		1500/3	5753	0	
10		1600/4 1700/4 1800/4	1000 1000 80	0 0 C	
11		1500/5 P1800	1000	F	A 0.132
12		1500/5 P600 P900 P1800	 5000 1200 203	 0 0 F	A 0.133
13		1600/4	1284	C	G 1115
14		1500/4	1000	F	OH
15		1600/5	1900	C	T300/1600
16		1600/5	409	C	

TEST LOG (cont)

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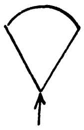
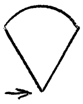
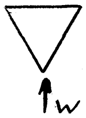
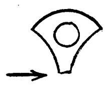
17		1500/5 P1800	300	F	A 0.140
18		1800/4	1950	C	G 1500
19		1700/3	530 W	C	
20		1500/3	1000	0	BT
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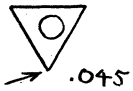
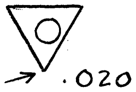
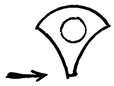
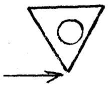
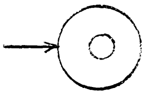
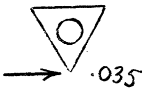
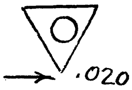
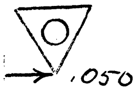
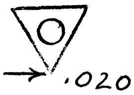
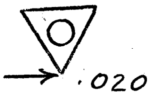
1		1600/4 +10/100	866	C	
2		1600/4 +10/100	1147	C	
3		1500/4 +10/100	575	C	BT
4a	Fatigue	54K	5200	F	
4b	Specimens	54K	10400	F	40.5K 82000

TEST LOG (cont)

Specimen Number (1)	Cross Section (2)	Cycle (3)	Number of Cycles (4)	Type of Failure (5)	Remarks (6)
5		1500/4 +10/100	1326	C	
6		1500/4 +10/100	1990	C	
7		1600/3.5 +10/100 to 1800	2700	G	
8	(Defective)				
9		1600/4	2863	C	R
10		1600/4	3787	C	Check II
11		1600/4	2580	C	
12		1600/4	3162	C	G 736
13		1600/4	2204	C	G 2072

TEST LOG (cont)

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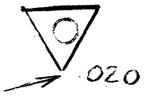
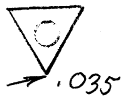
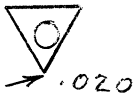
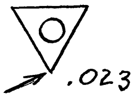
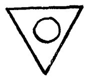
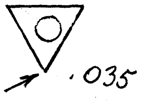
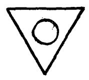
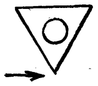
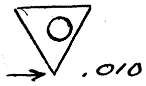
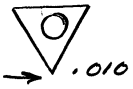
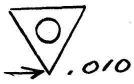
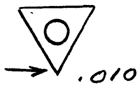
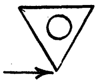
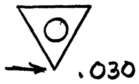
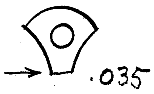
14		1600/4	2707	C	G 2604
15		1600/4	3003	C	G 2820 R
16		1600/4	2518	C	R
17		1600/4	4850	O	Check I
18		Fatigue 64K	7200	F	54K 103300
19		1600/4	1825	C	R
20		Fatigue 64K	4300	F	37K/217100 42K/11000 48K/35600 54K/10000 59K/10400
21		1600/4	4430	C	

TEST LOG (cont)

Specimen Number (1)	Cross Section (2)	Cycle (3)	Number of Cycles (4)	Type of Failure (5)	Remarks (6)
22	(Defective)				
23		1600/5	2962	C	
24		Fatigue 59K	52900	F	
25		1600/5 P.F.	1562	C	54K/5000
26		1600/5	1960	C	53K/52000 59K/12000 64K/1000 70K/1000 75K/500
27		X P.F.	——	F	53K/52000 59K/11300
28		1600/5 P.F.	1594	C	53K/52000 59K/12000 64K/1000 70K/1000 75K/500
29		X P.F.	——	C	53K/52000 59K/12000 64K/1000 70K/1000 75K/300

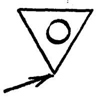
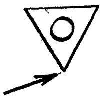
TEST LOG (cont)

Specimen Number (1)	Cross Section (2)	Cycle (3)	Number of Cycles (4)	Type of Failure (5)	Remarks (6)
30		1600/5	1973	C	
31		1600/5	2764	C	
H.S. 21 (Vitallium) [Cast]					
1		1500/3.5 +10/100	1000	C	BT
Inconel					
1		1500/3 +10/100	1450	C	G 1150
2		1500/3 +10/100	2730	C	
3		1500/3.5 +10/100	428	C	
4					

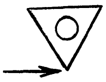
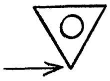
TEST LOG (cont)

Specimen Number (1)	Cross Section (2)	Cycle (3)	Number of Cycles (4)	Type of Failure (5)	Remarks (6)
5					
6		1600/4	7449	C	
7					
8					
9					
10					
11					
12					

TEST LOG (cont)

Specimen Number (1)	Cross Section (2)	Cycle (3)	Number of Cycles (4)	Type of Failure (5)	Remarks (6)
13					
S-816 Alloy (Wrought)					
1		1500/4 P700 No load	1788 18391	O C	A 0.08 N +100/5108 +100/10000
2		1500/4 P1100 to P700	2657	F	A 0.08 N
3		1700/4	2256	C	
4		1700/4	2550	C	
5		1600/4	3870	C	
6		1500/4	2630	C	

TEST LOG (cont)

Specimen Number (1)	Cross Section (2)	Cycle (3)	Number of Cycles (4)	Type of Failure (5)	Remarks (6)
7		1500/4	13280	C	
8		1600/4	7497	C	