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SUMMARY REPORT NO. 2

THERMAL SHOCK OF ALLOYS

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INTRODUCTION

In the analysis of the operation of modern aircraft gas turbines, the limiting length of operating time between overhauls is considered to be one of the most important factors. The limiting overhaul interval is generally conceded to be critically dependent on the durability of the buckets of the gas turbine. These buckets are subject to both high mechanical stresses and high temperatures, with a certain amount of fatigue in addition. Bucket design usually considers only creep and stress-rupture life, with fatigue usually omitted because of inadequate information on the amplitude and/or frequency of vibration present. The analysis of the mechanical stresses can be performed on the basis of centrifugal forces, but it is somewhat difficult to determine the exact region of the highest temperature on the bucket. However examination of the oxide pattern on the bucket shows that a zone about as long as one-third the bucket height, located somewhat closer to the tip than to the root of the bucket, is the hottest region. The actual operating temperature has been found in only a few turbines.

It appears that it should be possible to design a turbine bucket from the known properties of materials and conditions of load and temperature. However, such design does not take into account the presence of stress raisers such as lateral cracks, because it is known that such cracks are not present prior to turbine operation. The design further assumes that no cracks will appear during operation. If such cracks do develop, they can be harmful in four ways: first, by decreasing the area acting, and thereby raising the nominal stress; second, by acting as surfaces for the growth of oxide; third, allowing a consequent increase of stress as the oxide forces the crack open; and fourth, by serving as stress raisers to nucleate fatigue failures. It is important to note that evidence exists to indicate that cracking does occur in turbine buckets during operation.

It has been shown by I. Perlmutter[1] of WADC that small cracks on the leading edges of turbine blades may have been responsible for nucleation of fractures in some cases where failures might not otherwise have occurred at all or not as quickly. The belief that some cracking in turbine blades might be caused by thermal strains was felt to be substantiated by the following observations, made by one of the authors during a series of visits to establishments working with turbine blades:

a) Thermal-shock tests on single vanes have caused cracks superficially similar to those found in service.

b) Some turbine blades which had been removed from a turbine after operation manifested cracks nearly equally spaced along the length of the leading edges. Centrifugal force alone might possibly have produced the cracks, but it would not be expected that the cracks would then be equally spaced. Thermal stresses producing a uniform tension along the leading edge, however, would produce equally spaced cracks.

c) Other turbine blades or nozzle vanes were observed to have buckled along the trailing edge. This buckling could be caused only by compression, indicating that the leading edge was in tension, which provided a force of reaction for the compression.

In summary, these observations suggest that leading edges are in tension during thermal stressing, that the tension is nearly uniform, and that cracks can be produced by repeated thermal straining. It is also possible for trailing edges of buckets to be placed in tension by thermal strains, depending on the pattern of flow of hot gases around the blade, and on whether the strains originate as a heating or cooling operation.

In endeavoring to ascertain the cause of cracking at the edges of turbine buckets, it was natural to examine the nozzle diaphragm of the gas turbine, because the diaphragm vanes fail almost exclusively by cracking. Figure 1a shows a photograph of cracks found along the leading edges of a vane from a nozzle diaphragm. These vanes are known to be subject only to stresses that are thermal in origin; there is no rotation nor other mechanical process present that is capable of exerting forces on the vanes of the diaphragm. One of the authors has seen cases where cracking has progressed half through the chord of a vane. The result of the foregoing observations led to the premise that thermal effects might be responsible for the cracking of leading edges of turbine blades, at least in part.

WADC consequently decided to sponsor research on cracking of metals by thermal stress induced by unsymmetrical cooling of a metal specimen. The basic test rig had been assembled by the sponsors and was loaned to the University of Michigan for the research.

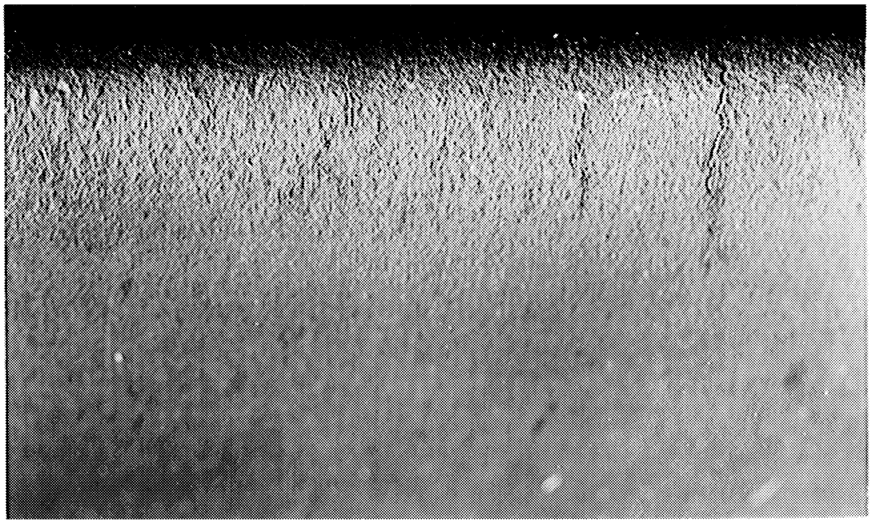


Fig. 1a. Photograph of Cracks in Vane of a Nozzle Diaphragm

Fig. 1b. Photograph of Three-Vane Assembly From a Nozzle Diaphragm From Which Fig. 1a Was Taken

Several definitions are now given of terms as they will be used in this report:

Stress. Stress is the ratio of the force on a surface to the area of the surface for areas so small that the force is substantially constant over the small area. Internal stresses are defined as if the member were sectioned so as to expose the interior surface on which the stress acts.

Thermal Stress. A thermal stress is one produced by a variation of temperature in a member or an assembly of members as measured from a fiducial temperature. Turbine blades are essentially unrestrained in thermal expansion by other members, so that thermal stresses are created only by a variation of temperatures from point to point within the blade and not by a raising or lowering of the bulk temperature of the blade. It is assumed that the material of the blade is sufficiently homogeneous that differences in coefficient of thermal expansion in the constituents of the blade alloy do not produce appreciable stresses as the bulk temperature is altered. It is also assumed that the material is isotropic in its thermal-expansion properties, so that grains do not expand differently in different crystallographic or textural directions. Nozzle vanes are constrained by the shroud rings, but it can be shown that the forces of such constraint are small, so that the nozzle vane is thermally stressed chiefly by variations of temperature in the vane, and negligibly by fluctuation of the bulk temperature. The magnitude of the thermal stress is therefore a function only of the thermal strain (q.v. below) and Poisson's ratio at the temperature in question.

Strain. Strain is the ratio of the elongation between two points in a member to the free distance between the points at the temperature in question. It is not necessary to utilize the concept of natural strain in this discussion.

Thermal Strain. Thermal strain is strain produced by temperature effects only. It is a function only of coefficients of thermal expansion and distribution of temperature in the entire member in question.

Thermal Shock. Thermal shock is a state of relatively large thermal strain produced by a nonequilibrium distribution of temperature, usually induced by a rapid change in heat transfer through the surfaces of the member.

Repeated Thermal Shock. Repeated thermal shock is thermal shock produced over and over again in a fairly reproducible manner from cycle to cycle of thermal shock. A thermal shock is first induced and then allowed to die away as thermal equilibrium is restored; then the original thermal conditions are re-established relatively slowly, after which the thermal shock is again set up, and so forth.

Thermal Fatigue. Thermal fatigue is a fracture or other damage produced by thermal stresses (whether or not induced by thermal shocks) which produce a cyclical variation of stress with time, just as mechanical fatigue is a fracture or other damage produced by cyclical stresses of mechanical origin that vary with time.

Crack. A crack is a fissure of specified length in the surface of a member. For convenience of observation, the length should be readily determinable. For purposes of this report, a crack is defined as a fissure extending completely across a relatively narrow face of a specimen.

Previous investigations of cracking by thermal stress can be classified according to the ductility and type of materials tested. Thus Norton[2] and Lidman and Bobrowsky[3] investigated brittle ceramics in the temperature range where plastic flow was negligible; Whitman, Hall, and Yaker[4] studied metals with reasonable ductility, say, above 5% elongation in a 2-inch gage length for room-temperature tensile tests; and Avery and Matthews[5] studied brittle metal castings. Based on the work on ceramics, a criterion for ordering the thermal-shock resistance of materials was set up, namely:

$$\frac{ks}{\alpha} = \frac{\text{(thermal conductivity)(strain at failure in tensile test)}}{\text{(coefficient of thermal expansion)}}$$

Other investigators have introduced Poisson's ratio (that poorly reproducible physical quantity that varies from investigator to investigator). A very large advance was made when it was realized that the original NACA criterion given above was meaningful only if the thermal conductivity were not too small nor the severity of the shock excessively great. A truer criterion of susceptibility to thermal cracking should, then, incorporate the thermal conductivity raised to a power between zero and unity.

In practically all treatments of the problem, emissivity of the surface oxide was either considered to be zero or was lumped into the convection heat-transfer coefficient. Variation of properties of materials during the shocking process has generally been ignored.

With this background, it was decided to seek the following results:

1. A thermal-cracking apparatus using air as the shocking medium.

2. A reproducible thermal-shock test.

3. An ordered list of high-temperature alloys with respect to susceptibility to thermal shock.

4. Insight into the mechanism of formation of thermal cracks.

The research described in this paper was performed from 1951 to 1953 at the Engineering Research Institute of the University of Michigan, Ann Arbor, Michigan. Acknowledgement is made to Professor Paul F. Chenea, now of Purdue University, for his assistance as co-supervisor during much of the project.

APPARATUS

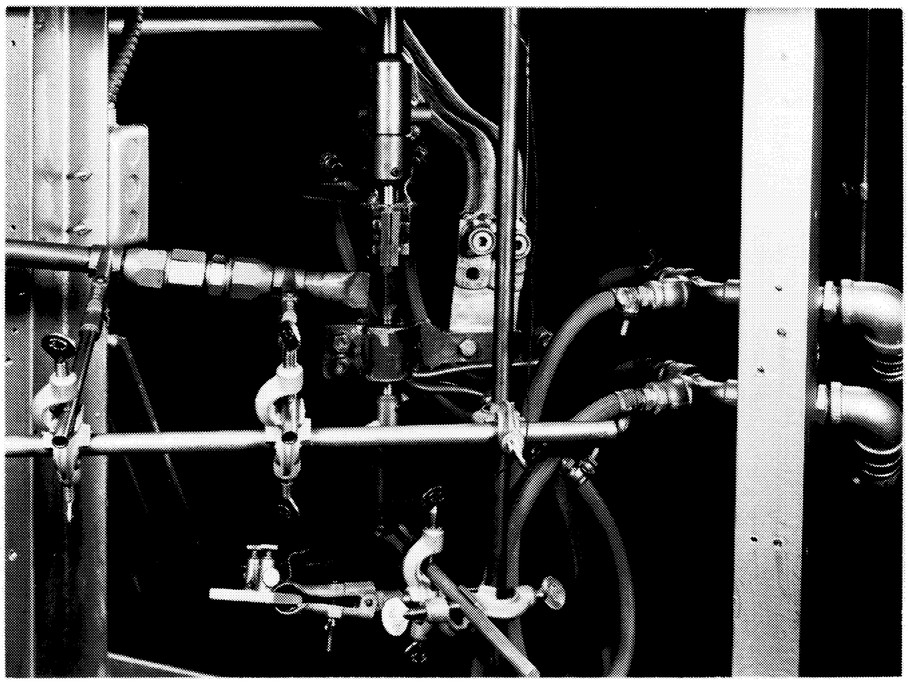
Test-Rig

The apparatus employed during this investigation was borrowed from the WADC and subsequently altered a number of times to fit the immediate needs of the studies. In essence, the test specimen was heated to test temperature by electric-resistance heating at a relatively slow rate and then rapidly cooled by an air blast from a nozzle. In general, the heating time was about one minute and the cooling time was five seconds.

The voltage across the specimen was adjusted to yield the proper heating time, with the result that the rate of heating was most rapid at the lowest specimen temperatures and slowest as the maximum temperature was approached. The heating rate at the maximum temperature was about 5°F/minute. This heating time was maintained constant during each test by appropriate adjustment of the voltage as required. The instrument for indicating temperature also served as controller to cut off the voltage and to open the solenoid-actuated air valve for cooling when the maximum temperature was achieved. The duration of the cooling-air blast was governed by an electric timer.

The original equipment is shown in Figs. 2a and 2b. The lower specimen grip could be attached to a lever loaded by dead weights to simulate the centrifugal loading in the turbine, but practically all tests were made without this dead load. The first major change was the addition of a plenum or accumulator tank to maintain the air flow relatively constant during the cooling period. It was also found necessary to enlarge the air-supply system in order to increase the severity of air cooling and to make the cooling more uniform over the test section of the specimen. The modified equipment is shown in Fig. 3.

The next modification of the apparatus was the installation of a second setup on the original test frame (Fig. 4), which used a total-radiation pyrometer instead of the previously employed thermocouple inserted in an axial hole in the specimen. The specimen holder was made integral with the air nozzle to improve the accuracy of location of the nozzle with respect to the



Grip

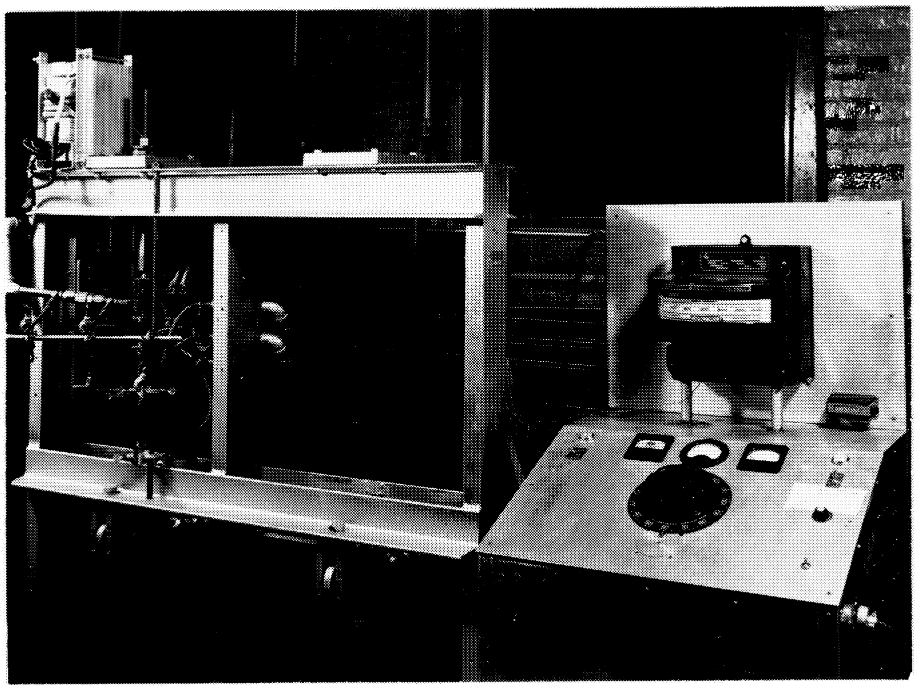
Cooling nozzle

Specimen

Water-cooled electrode

Supporting bars

a) Cooling nozzle directed at specimen



Step-down transformer

Temperature indicator and controller

Cycle counter

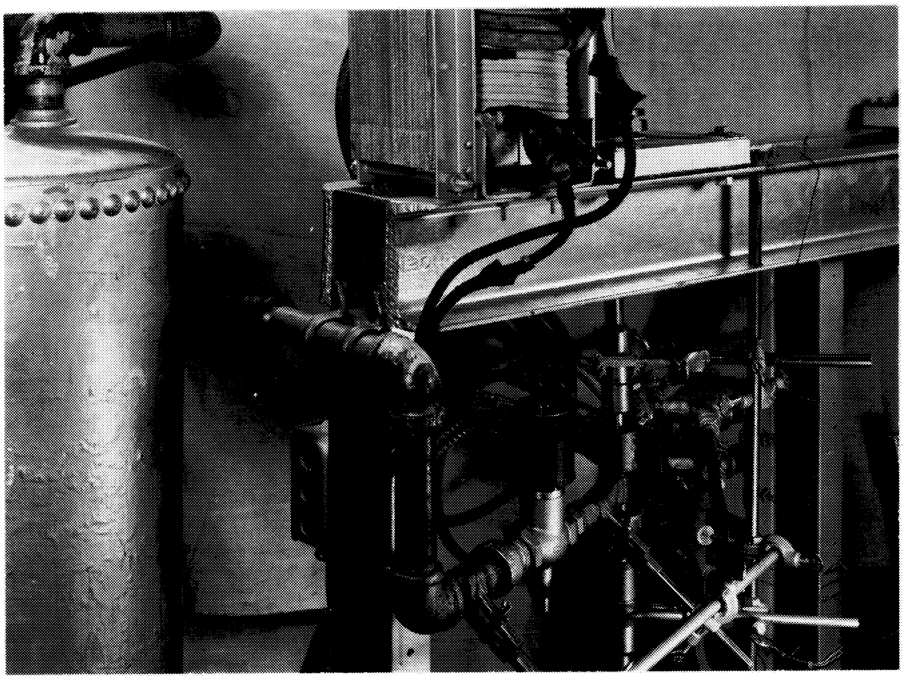
Voltmeter

Ammeter

Variable transformer

b) Test frame and control panel

Fig. 2. Test Setup



Step-down transformer

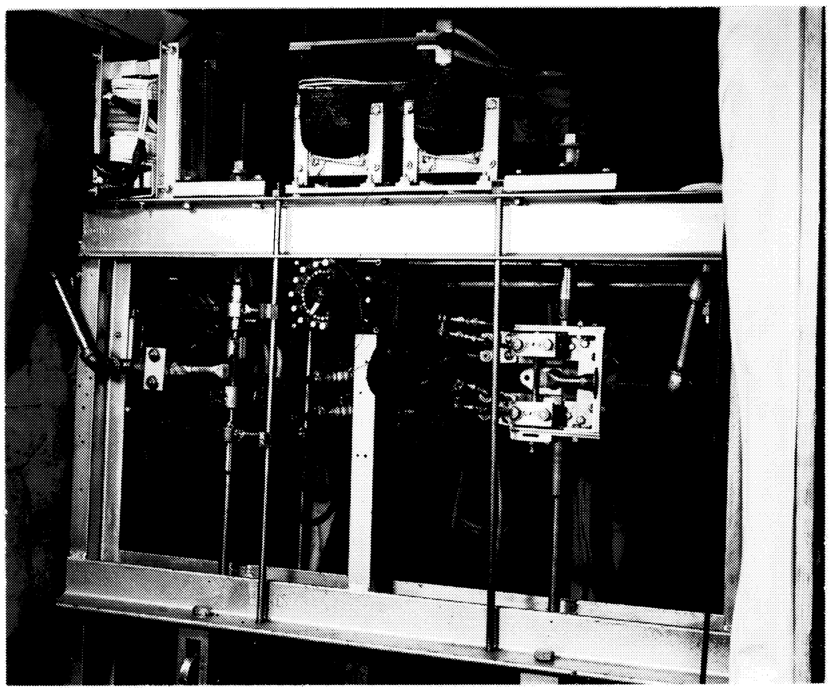
Accumulator tank

Valve

Specimen Nozzle

Fig. 3. Test Setup

Transformers



Levers

Fig. 4. Interior of Test Rig Showing Setup with Two Specimens

specimen in consecutive tests (Fig. 5). Lack of allowance for axial expansion, however, resulted in bulging of the specimen when heated (Fig. 6). The specimen holder was altered to permit axial expansion of the specimen, giving rise to the apparatus shown in Fig. 7.

The entire test frame was enclosed in a sound-minimizing shelter (Fig. 8) with the control panel next to it (Fig. 9). Two plenum tanks were used, one for each specimen.

Cracks were observed by means of a measuring telescope (Fig.10) that was swung away from the heated specimen when observations were not in progress.

The air nozzle was patterned after a protype precision nozzle with removable walls. Different wall thicknesses enabled severity of the air blast to be changed. The velocity of exit air was usually just above Mach 1 as shown by schlieren measurements.

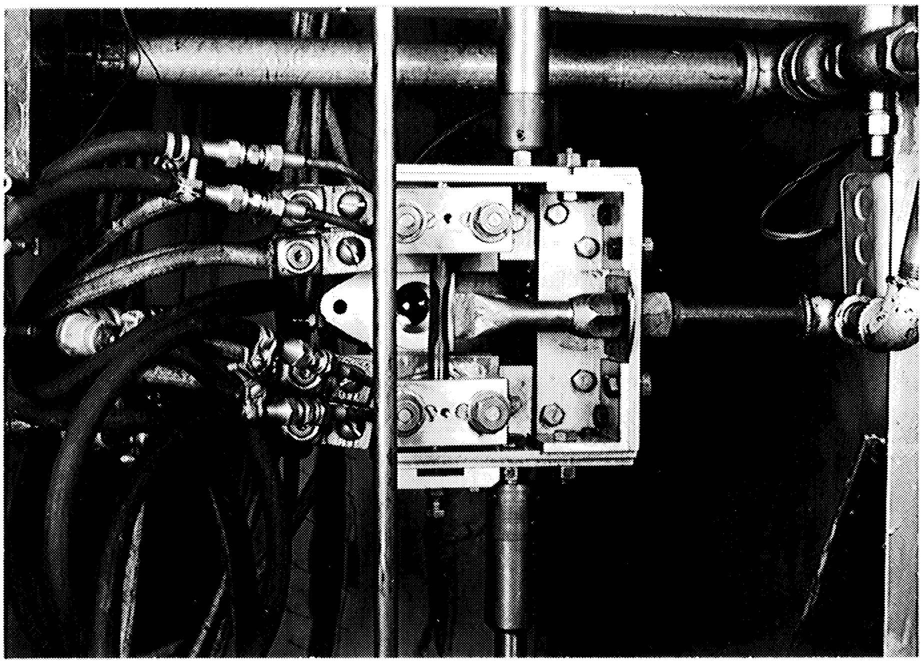
Specimen

Several types of specimens were utilized in early tests to find a shape of cross section which would permit easy detection of cracks, could be manufactured to reproducible dimensions, and would allow temperature measurements to be made with reasonable accuracy. Among those tried were round, square, diamond, hollow-cut, vee, and triangular cross-sections (see Fig. 11). The shape finally adopted is shown in Fig. 12. An axial hole was drilled for thermocouple insertion on the first specimens, but with the use of the total-radiation pyrometer the hole was abandoned. The pyrometer sighted on the flat back of the triangular specimen. A gage was built onto the specimen to ensure that the back of the specimen was perpendicular to the line of sight of the pyrometer.

The specimens were machined from bar stock or castings of 1/2-inch diameter or larger. The test edge of the specimen was machined to a thickness of about 1/32 inch, the thickness being uniform along the test section. This thickness was measured by a 5X measuring telescope.

Fatigue specimens were occasionally employed to determine mechanical fatigue strengths at room temperature at high stresses. Figure 13 illustrates the shape of the specimen employed. Thermal-shock specimens were sometimes prefatigued prior to shocking. The same fatigue machine (Fig. 14) was used for both purposes, sometimes with a speed-reduction drive to prevent overheating of the specimen during the fatigue operation. The specimen was fatigued as a simply supported rotating beam, loaded by dead weights. The

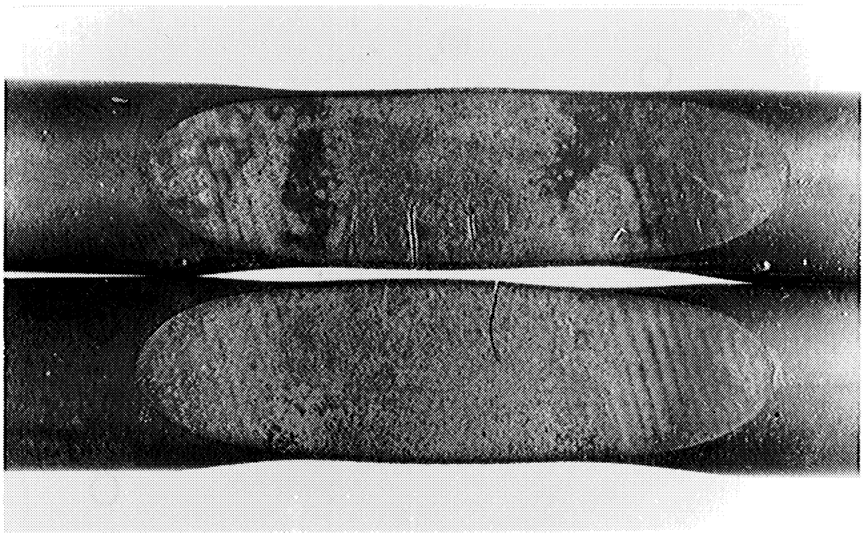
Radiation Pyrometer



Nozzle

Support

Fig. 5. Details of Setup With Radiation Pyrometer and Specimen Supports



Grooved Cracks

Cracks

Fig. 6. Compressive plastic flow produced by tests in rigid specimen-nozzle holders. Specimen No. 39 (top) and No. 43 (bottom), about 2X scale. Specimen No. 39 shows the face at which the air jet pointed, whereas Specimen No. 43 shows the face adjacent to the cooled face.

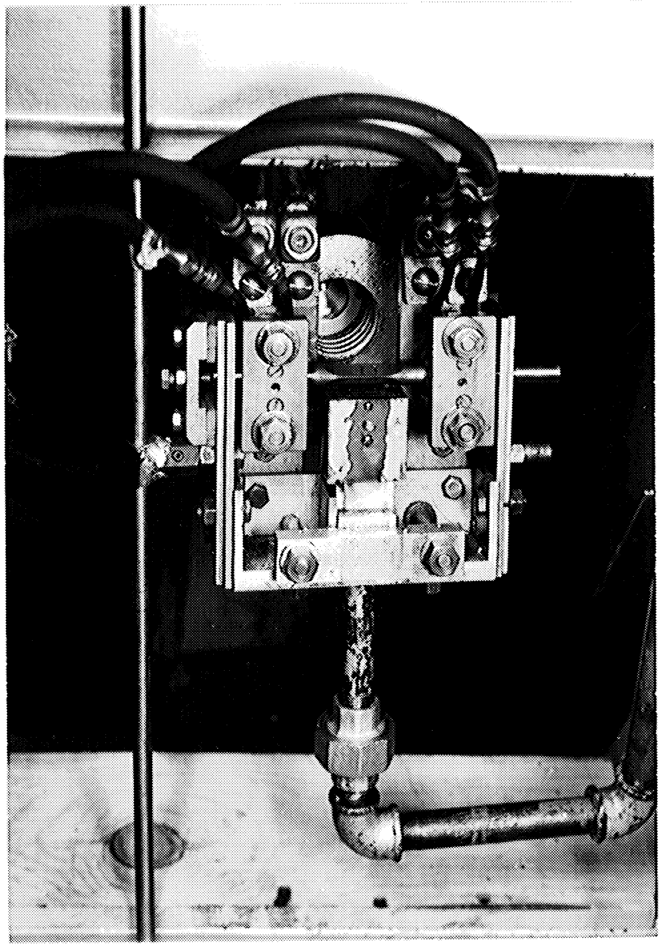
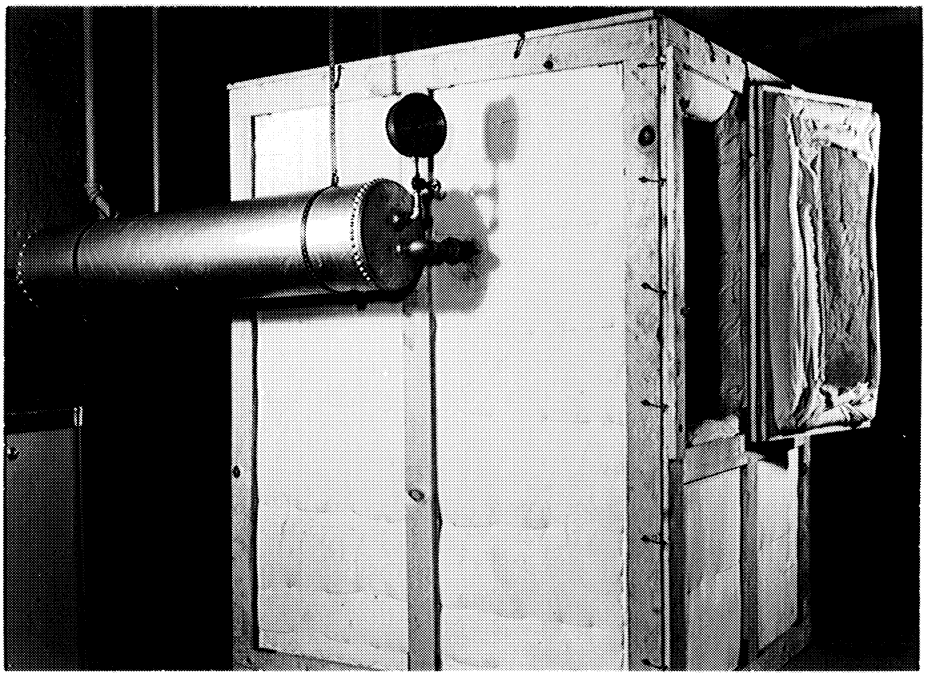


Fig. 7. Front View of Specimen Holder, Specimen, Air Nozzle, and Radiation Pyrometer.

Plenum



Inspection Door

Fig. 8. Exterior of Sound-Minimizing Chamber Surrounding Test Rig

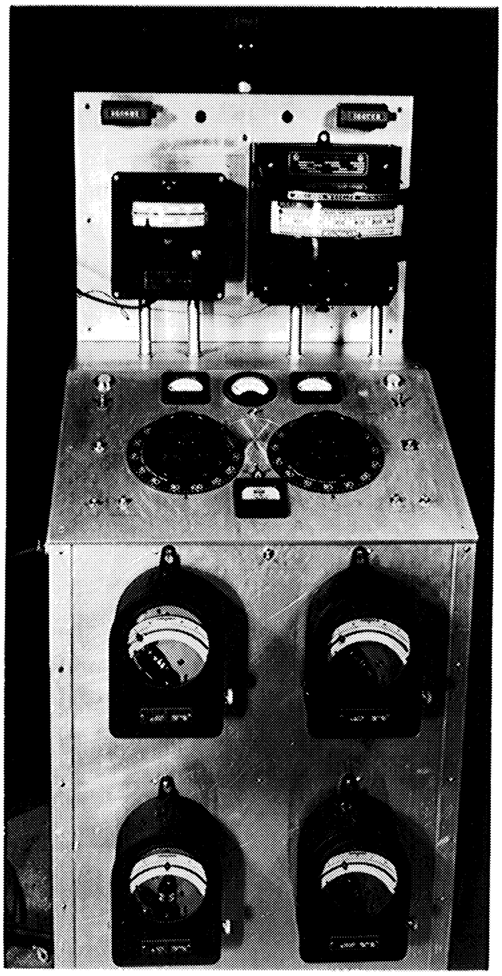


Fig. 9. Control Panel

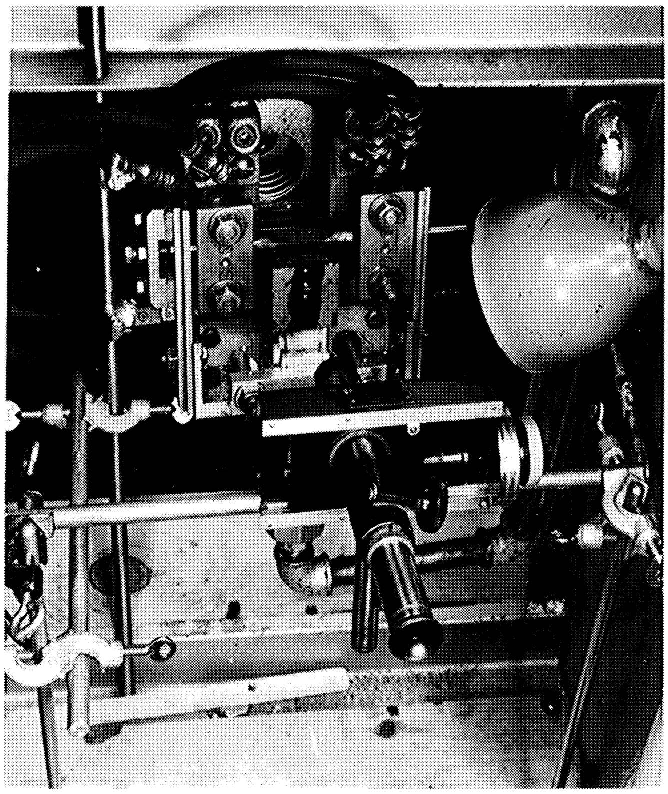
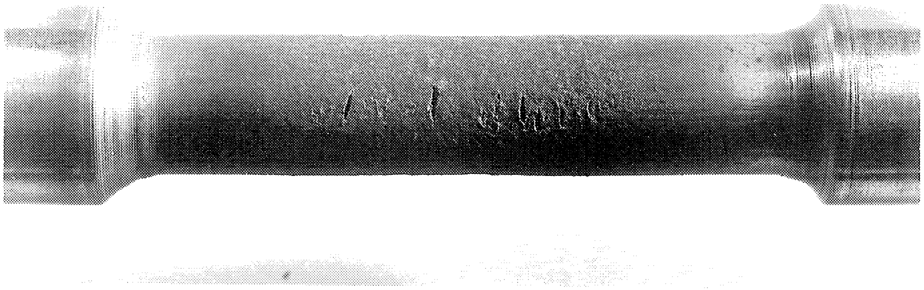
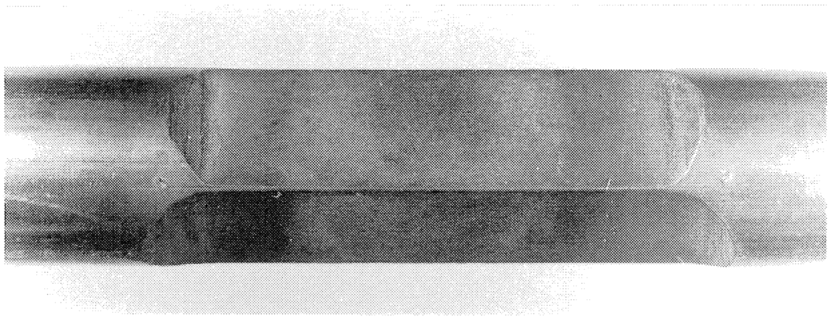


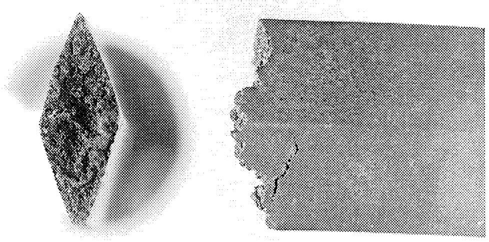
Fig. 10. View of Specimen Holder With Measuring Telescope in Position to View Specimen



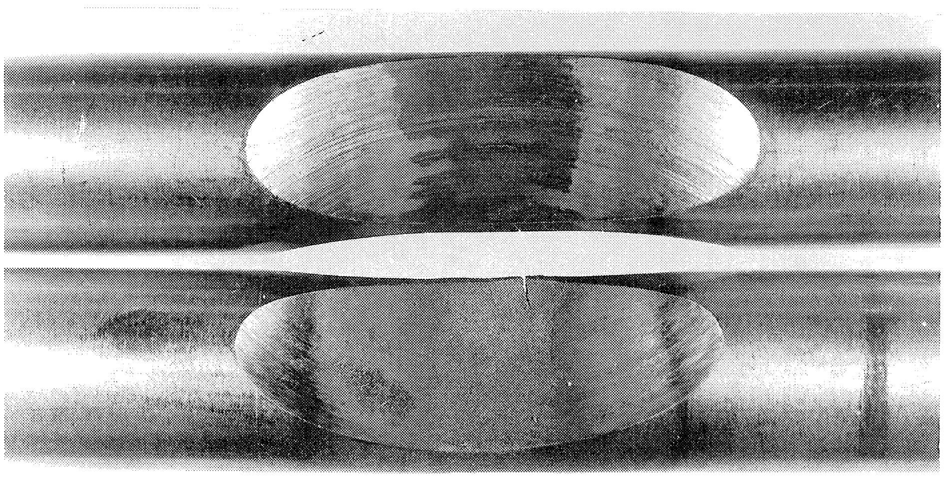
a) Thermal-Shock Specimen of Round Cross-Section, Showing Grooves After Test. Type 347 Stainless Steel



b) Thermal-Shock Specimen of Square Cross-Section



c) Diamond-Shaped Specimen of Type 304 Stainless Steel, Fractured During Overheating in Thermal-Shock Test. Axial Load was Caused by Lower Electrode and Grip.



d) Thermal-Shock Specimens of Shallow-Cut Cross-Section. Top - Type 347 Stainless Steel. Bottom - Inconel

Fig. 11

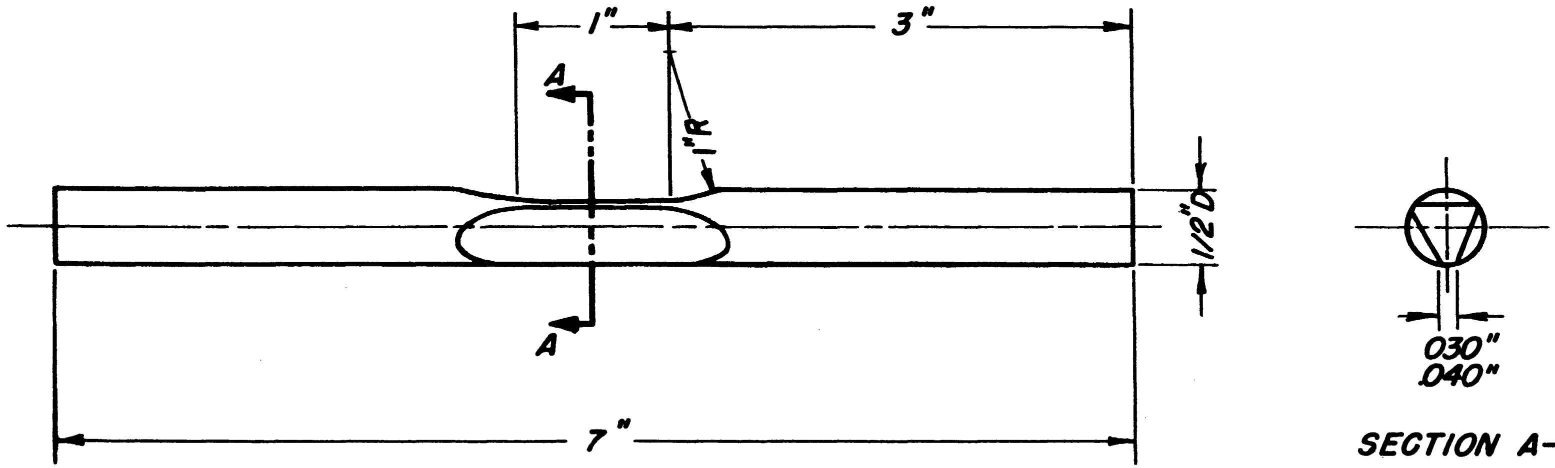


FIG. 12

THERMAL SHOCK SPECIMEN

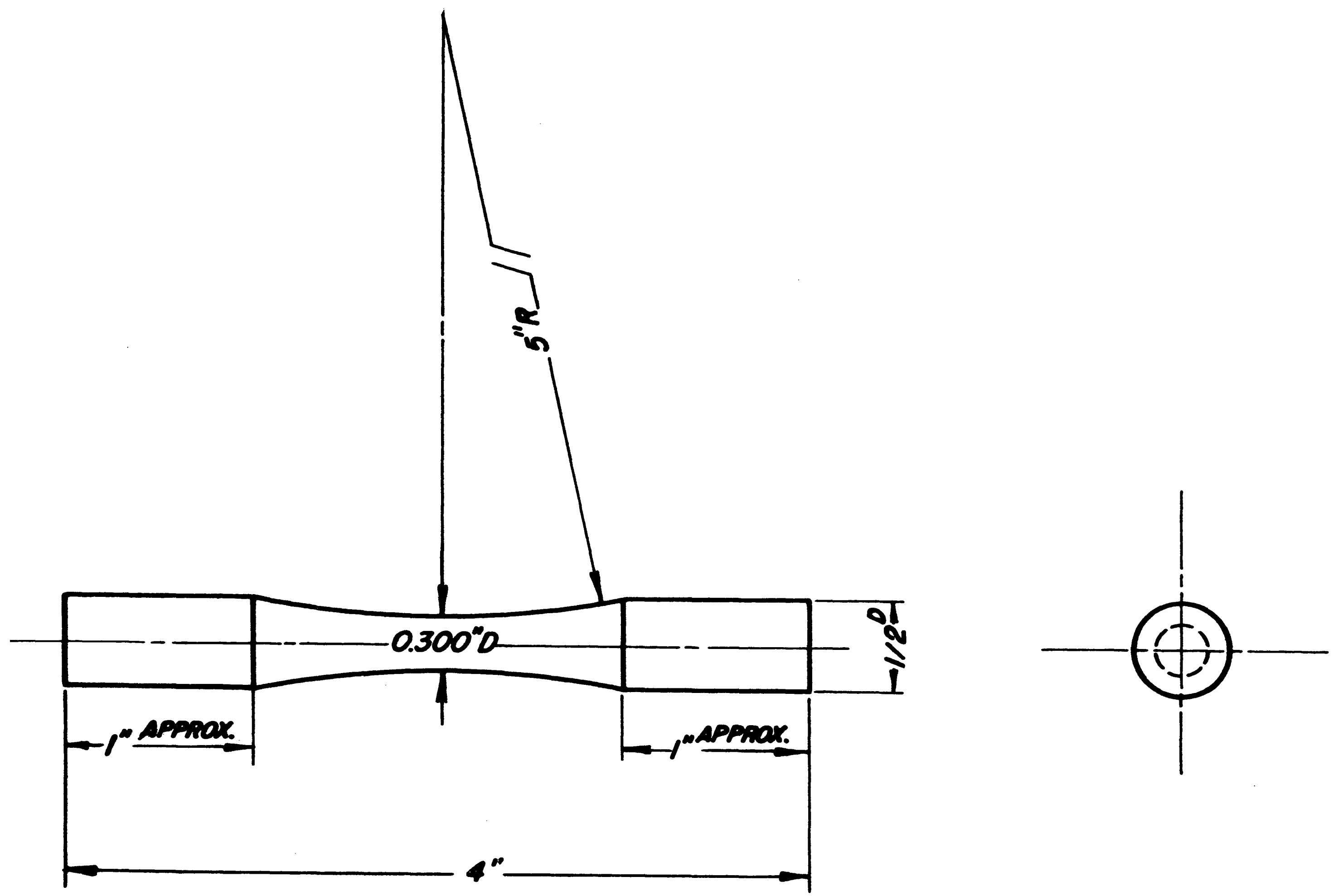


FIG. 13

FATIQUE SPECIMEN

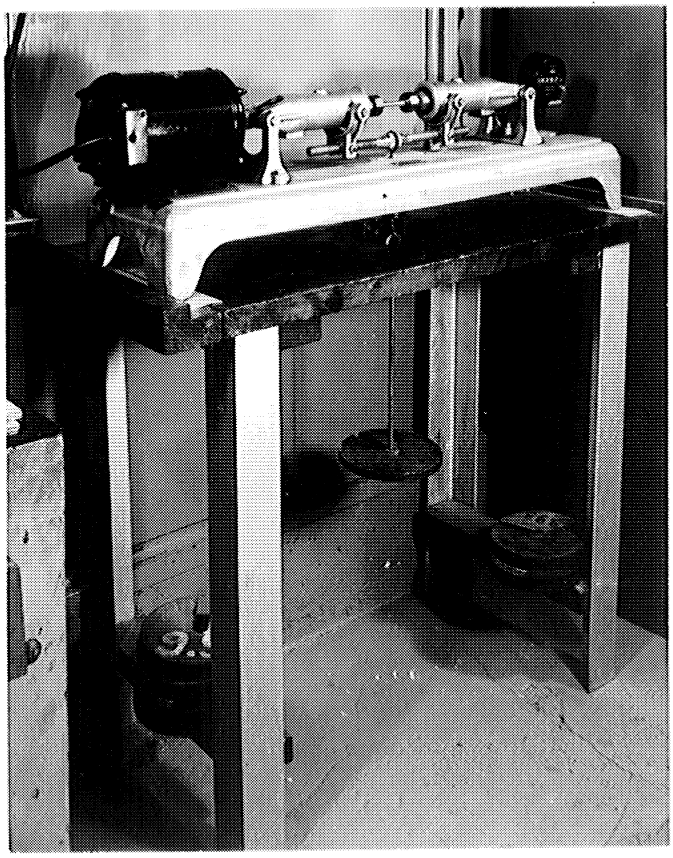


Fig. 14. Low-Speed Fatigue Machine (1800 rpm)

test specimen, of course, possesses three axes of symmetry, so that it has the same moment of inertia with respect to any plane through the axis of the specimen.

Procedure

The specimen, after possible mechanical or thermal pretreatment, is measured, inserted, and positioned in the specimen holder. The radiation pyrometer previously calibrated against a specimen of the same material but with a thermocouple inside, is sighted on the back of the specimen. The pyrometer is calibrated again at the conclusion of the test, and the test temperature is taken as the average of the two calibrations. The heating voltage is adjusted manually so that the heating time is one minute. Subsequent variations of line voltage are compensated for by manual adjustment of an autotransformer which feeds the main step-down transformer. The electrodes at the ends of the specimen are water-cooled, thus causing a flow of heat along the axis of the specimen. This loss of heat is negligibly small compared to the cooling by the air blast, so no provision was made to prevent this heat flow.

ANALYSIS

Factors to be Considered in Analysis

A preliminary analysis of the thermal-shock process reveals the following general features (the details of this analysis are given in Ref. 5):

1. Heat Transfer by Conduction. The distribution of temperature by conduction alone is a fuction of the thermal diffusivity of the specimen material, where $\mathcal{K}$, thermal diffusivity, is the thermal conductivity/specific heat per unit volume.

In dimensionless form, the diffusivity may be related to the dimensions of the specimens and the time of observation. Thus

$$\Pi_1 = \frac{\alpha t}{x^2}$$

is dimensionless, where t = time,

x = any characteristic length, and

Π_1 = first dimensionless parameter.

In general, even for the simplest theoretical cases the temperature at any point in the heated specimen is a complicated function of Π_1 and the distance from the boundary to the point in question. About all that can be stated for a nonspecific case is that larger values of Π_1 make the variation of temperature in the specimen more gradual, other conditions being held constant. Similarly, the thinner the specimen, the more gradual is the temperature variation from point to point in the specimen.

2. Heat Transfer by Radiation. The loss of heat by radiation is a function of the emissivity of the oxide coating on the material

$$\Delta Q = \sigma\varepsilon(T^4 - T_o^4) \quad ,$$

where ΔQ = rate of heat loss,

σ = a constant

ε = the emissivity of the surface material,

T = the temperature of the specimen, and

T_o = the temperature of the surroundings.

The amount of heat lost by conduction in the test specimen greatly exceeds that lost by radiation because of the large heat-conduction area leading to the water-cooled electrodes on the ends of the specimen. To a first approximation, the heat lost by radiation may be neglected for the test specimens used. In the gas-turbine bucket, the ratio of surface area to cross-sectional area is much larger than in the test specimen. Also, the ends of the turbine bucket are not as different in temperature from the hottest zone as are the ends of the test specimen. These two factors would tend to indicate that radiation plays a greater role in the turbine than in the thermal-shock test. On the other hand, the material surrounding the turbine bucket is at a much higher temperature than the material surrounding the test specimen. These effects would be partly self-cancelling, probably permitting neglect of the radiation loss for the turbine bucket also.

3. Heat Transfer by Convection. The loss of heat by forced convection in the air blast can be related to the loss by conduction as the dimensionless parameter

$$\Pi_2 = \frac{hx}{k} ,$$

where h = the heat-transfer coefficient for forced convection and

k = the thermal conductivity.

The variation of temperature with distance from the boundary will be more gradual the larger the value of Π_2. The coefficient h is a function of the speed of the cooling-air stream, the direction of the air stream, and the flow regime (turbulent or laminar). For all test conditions, flow was turbulent. Conditions were similar to those in the turbine in this respect. The direction and location of the jet with respect to the specimen were varied, with best results observed when the jet was directed at the thin edge parallel to the uncooled flat face. The velocity was slightly supersonic, as determined by observations of Mach angle by means of a schlieren setup.

4. Coefficient of Thermal Expansion. The strains or stresses set up by given thermal gradients are higher the greater the coefficient of thermal expansion, all other factors being constant. The coefficient of thermal expansion enters into a dimensionless parameter as:

$$\Pi_5 = \alpha \Theta_o ,$$

where α = coefficient of thermal expansion and

Θ_o = any characteristic temperature on the specimen.

5. Poisson's Ratio. Larger thermal stresses are introduced in restrained members by large values of Poisson's ratio than by small ones. This may be seen qualitatively by examining a specimen restrained on all sides. An increase in temperature tends to extend the material in, say, one direction. The restraint on the expansion tends to bulge the specimen on all sides. This bulging is highest with largest Poisson's ratio. The restraint in the directions of bulging consequently introduces stresses that are largest for largest amounts of bulging.

The variation of Poisson's ratio with temperature was found in the literature only for Inconel and stainless steel[5]. There is some doubt in the writers' minds about the validity of these data. Values of Poisson's ratio in excess of 0.5 are exhibited, indicating that the specimen decreased in volume under tensile stress. It is consequently not possible at this time to determine the variation in stress produced by these unknown values of Poisson's ratio.

6. Stress-Strain Properties. The yield points at the maximum temperatures of test are so low for the materials used that some plastic flow may be expected. The amounts of plastic flow for the same temperature distribution, coefficients of heat transfer, and thermal expansion are different for materials with different stress-strain relations. The stress-strain relations are incompletely known for the materials under study, but rough classifications can be made of relative yield strengths. Those materials with the lowest yield points will offer less restraint to the specimen and consequently will give rise to smaller thermal stresses.

Any dimensionless parameters that may be set up to account for variations in stress-strain properties are too complex for use unless the stress-strain curve is idealized to, say, two lines, an elastic and a plastic, or to a simple exponential curve. It is probably as well to use the yield point from a short-time tensile test, which can be expressed in dimensionless form as a ratio of yield stress to a constant characteristic stress. It is also important to characterize the yield point by the strain at which yield occurs, for the stress-strain curve may not be linear.

Discussion of Analysis

1. Comparison of Modes of Heat Transfer. Neglecting radiation effect, heat transfer in the test specimen is accomplished by conduction and forced convection. It is known that the test specimen has a relatively higher ratio of heat loss by conduction to convection than in the turbine blade (for the same velocity of cooling air as in the turbine) because of the cooled electrode at the ends of the specimen. For this reason, the velocity of cooling air past the specimen was made very high in order to reduce the discrepancy in the conduction-convection ratio.

2. Discussion of Material-Property Data to this Point. The strains set up by thermal expansion are given by the first and second derivatives of temperature with respect to distance, coefficient of thermal expansion, Poisson's ratio, and yield point (stress and strain). In turn, the temperature gradient and its rate of change are determined by thermal diffusivity, thermal conductivity, and specific heat on a volume basis.

All other factors being constant, the materials most resistant to thermal cracking possess

Large	Small
Diffusivity	Poisson's ratio
Conductivity	Expansivity
Strain at fracture	Yield stress

3. Discussion of Properties Possibly Pertinent to Failure. The failure mechanism is known to be progressive in nature because single thermal-shock cycles do not produce cracking. Properties which have been proposed to govern failure are:

a) ductility in tension,

b) fatigue strength,

c) stress-rupture strength, and

d) corrosion-fatigue strength.

The progressive nature of the failure has been proposed to depend on the alteration of properties because of

a) plastic deformation,

b) exposure to elevated temperature, and

c) oxidation, with or without accompanying stress.

It is known that deterioration in physical properties preceding fracture in fatigue or stress rupture is of very rapid occurrence. For example, experiments on the stress-rupture deterioration of glass rods showed no sensible change in the strength of remaining rods when 20 per cent of a sample had failed in stress rupture.[6] It is consequently believed that it is not feasible to deteriorate a specimen just short of failure by stress-rupture loading and then to determine physical properties different from the original.

In general, however, it is thought that a specimen with higher stress-rupture strength, fatigue strength, and corrosion resistance, all these properties being constant with time and temperature, will be more resistant to thermal cracking.

4. Statement of the Problem. The elements which must be considered are outlined below.

A	B
External temperature	Specific heat
Air velocity	Thermal diffusivity
Specimen size and shape	Emissivity
Air properties	Thermal conductivity
Schedule of variation with time	

C	D
Thermal expansivity	Metal structure
Stress-strain relation	Chemical composition
Poisson's ratio	Initial stresses and strains

E	F
Stresses and strains	Tensile properties
Diffusion	Fatigue Properties
Chemical and metallurgical reactions	Corrosion-fatigue properties
Separation of surfaces	(Creep properties)

Table A lists the external conditions imposed on a specimen. These conditions are the boundary conditions on our problem. A given material possesses the thermal properties shown in schedule B, deformation properties shown in schedule C, and chemical-metallurgical properties shown in schedule D. These properties may vary with temperature (e.g. thermal conductivity), with time (e.g. emissivity), with stress (e.g. Poisson's ratio), or with any combination such as stress-time-temperature (e.g. metallurgical structure). Metallurgical structure, chemical composition, and initial stresses influence the rate at which other properties change with time. The combination of external conditions and material properties gives rise to the changes listed in Table E, viz., stresses and strains, dissolved elements, reaction products, and microcracks. These changes cause a failure to occur that is designated by one or more of the mechanisms listed in Table F.

It is impractical to endeavor to analyze the problem completely as a step-by-step progression through the tables presented. It is necessary to eliminate those factors of least significance; to group properties, conditions, or phenomena where possible; and to devise other simple test procedures that may give information on a group of variables where possible. For example, emissivity will be omitted because it affects only the radiation process, which has been shown to be small compared to convection and conduction.

It was apparent from the foregoing that the brute-force detailed analysis is impracticable because of the complexities involved. It was consequently decided to utilize the cooling shock as a tool to evaluate any deterioration in thermal-shock resistance which is caused by prior history of temperature and/or stress similar to the conditions in the turbine.

In summary, thermal cracking, as a physical process, is governed by certain material parameters. These parameters are known to be temperature-dependent, since the number of thermal-shock cycles required to crack a specimen varies with the temperature. Also, results tabulated later in this report show that a past history of repeated mechanical stressing alters the thermal-shock resistance of the materials investigated. It consequently becomes necessary to evaluate the effect of this stress and temperature history on the properties of the materials under study. It is not necessary to speculate on the local mechanism by which deterioration has occurred, since we are now interested only in a measure of the deterioration, not in its development.

The deterioration produced in the thermal-shock specimen during the process of performing the thermal-shock test is limited to the small amount of material located near a thin edge of the specimen, since only this portion is drastically cooled. A test to determine the extent to which deterioration has occurred must be sensitive to the change in properties of this small volume. Impact tests have been used to measure the change in properties of specimens under stress at temperature[6]. However, an impact test is not quite suitable, since it depends on the bulk properties of the entire cross section, rather than of the small portion near the edge.

Tests of such factors as rotating-beam fatigue and thermal shock itself would be suitable tests, since they emphasize properties in the region of interest in the specimen. An alternative procedure might be to cut smaller specimens from the regular specimen and use them for tensile testing. It is desirable, however, to avoid additional specimen preparation.

Consequently the type of test that is suggested is a two-stage affair. The first stage is a mechanical stressing to simulate the action of centrifugal forces in the turbine. The second stage is made up of thermal-shock cycles. This procedure is based on the fact that the intended schedule of operation of the turbine is known with respect to speed, gas temperature (and blade temperature, approximately), blade material, and blade dimensions. The usual zone on the blade in which failure occurs can be located. From these data, the conditions of operation of the blade material are known well enough to enable specimens of the same material to be subjected to a duplicate history of stress-time-temperature relations. If these specimens are subjected to thermal shock after experiencing whatever deterioration or damage may have occurred prior to the thermal shock, then a small number of thermal-shock cycles (corresponding to the number of times the actual turbine is expected to start up, shut down, and blow out) should suffice to determine whether the material can be cracked by thermal shock.

If the specimen cannot then be cracked, it may be expected not to crack in its intended service. The limiting conditions of damaging pretreatment (temperature, stress, and time) may be investigated in similar fashion for any material by determining what history is required to permit thermal-shock cracking to occur. In this way a sound basis for establishing limiting overhaul intervals may be determined.

A base line or datum may be set for the thermal-shock resistance of a material by determining its susceptibility (or lack of it) to cracking without previous exposure to stress or elevated temperature. This report is primarily intended to present data on the cracking of several high-temperature alloys without pretreatment, although some of the data were obtained after pretreatment.

It is realized that the method of experimentation and the analysis given above do not yield the fundamental parameters on which deterioration and consequent increase of ease of cracking are based. However, it is hoped that statistical analysis of the available properties of the materials to be tested will yield some evidence as to the most important of the possible influential parameters.

The question of severity of the thermal shock, as discussed by Manson in Ref. 7, is not as important as might be thought because this investigation is concerned with a known application. That is, it is known that the cooling medium is air at approximately atmospheric temperature and pressure as contrasted with, for example, water, liquid nitrogen, or hot combustion gases. It is known, also, that the velocity of the cooling air in a typical turbine thermal shock varies from about 200 mph to nearly sonic speed. For this reason, the range of severity of cooling shock to be encountered in practice is not expected to vary over a wide range for the intended application. The shock serves merely as a means of imparting a strain to a material and rather wide limits of severity do not greatly alter this strain. For this reason, an air nozzle was selected to serve as the standard in these tests, with an air velocity slightly below sonic.

RESULTS

Introduction

The results reported herein are concerned with the following types of information:

a) Number of cycles of repeated thermal-shock cooling required to cause cracking of a hot specimen of a given metal, compared to specimens of other metals.

b) Effect of temperature of specimen on number of cycles of thermal shock required to cause thermal cracking.

c) Effect of fatigue damage prior to shocking on number of cycles of thermal shock needed to crack specimen.

d) Effect of cold working prior to shocking on number of cycles of thermal shock needed to crack specimen.

e) Effect of edge width on number of thermal-shock cycles needed to crack specimens.

f) Reproducibility of results.

g) Variation of number of cycles of thermal shock needed to crack specimens with miscellaneous pretreatments of the specimen.

These results are intended to serve as a base line from which effects of temperature damage prior to shocking may be measured in later tests.

Several other results of a general nature are given before the specific numerical results.

General

a. Possibility of Cracking Metal Specimens by Thermal Strains Alone. Several investigators have shown previously that liquid quenches applied repeatedly to heated metal specimens could cause cracking: it has been well known that metals of small ductility and the usual ceramic materials have been cracked by single quenches of either air or liquid, but some question has existed as to whether single coolings of a material with a reasonable ductility, say, above 5% elongation in a 2-inch gage length, could be cracked by a single quench. It can be shown that even if the ends of a prismatic specimen are completely constrained and the temperature of the specimen is permitted to change by 2000°F, the strain induced in the specimen falls short of the failure strain of most metals. There are some cases where this statement is not true, however, as when an exceptionally large stress-raiser is present, or when the cross section of the specimen varies greatly along its length.

If a material cannot be cracked by a single thermal strain, why then can it be cracked by repeated thermal strains? Obvious reasons for the possibility of cracking by repeated straining are, first, working of the material to the point where its strain at failure is less than the thermal strain applied by the thermal shock; second, changes in metallurgical structures such that the new structure produced is deficient in ductility; and, third, deterioration of a sort encountered in stress-rupture tests, where corrosion and absorption of gases render the material susceptible to failure. Still another possible reason is the formation of microcracks at regions of local stress concentration until the joining of many microcracks produces a large crack or cracks. Whatever the actual mechanism (it may differ among materials) by which cracking is produced, the mechanism manifests itself as a deterioration of physical properties of the material. Thus, it may be pointed out that it is this progressive deterioration that must be minimized for a material to be resistant to cracking by thermal shock.

b. Effect of Rate of Loading on Physical Properties. It is well known that an increase in rate of loading during a tensile test results in an increase of yield point (and sometimes of ultimate tensile strength) and a decrease in ductility as measured by total elongation at fracture. At the start of this program of research, it was felt that a severe thermal shock would be equivalent to a rate of loading so high that the effective ductility of the material might be lowered to the point where a single shock could produce a crack in a material whose ductility, as measured by usual tensile techniques, should have precluded such cracking.

The rate of loading was judged by visually observing the rate at which the outer portion of the specimen changed from glowing brightness through dull red to black heat. Although the rate of cooling of the specimen directly under the nozzle was very high, most of the specimen cooled relatively slowly. As a result, it was assumed that the rate of loading, while high, was not sufficiently high to alter the elongation at failure appreciably.

1. Comparison of Materials

The alloys that were tested at maximum cycle temperatures of 1800°F, were Haynes-Stellite 21, S-816, and two lots of N-155. The cast Haynes-Stellite 21 alloy appeared to be most resistant to cracking, although the surfaces of most of the specimens were obscured by oxidation, which tended to conceal cracks. One lot of the N-155 alloy outperformed both the other lots and the S-816 alloy (heat-treated to conform to turbine-blade practice). The S-816 alloy possessed about the same susceptibility to cracking as did the poorer lot of N-155 alloy. The results in general are shown in Fig. 15.

Tests at 1700°F were conducted on cast Haynes-Stellite 21 alloy (both as-received and heat-treated to increase ductility), S-816 alloy (heat-treated to conform to turbine-blade practice), Inconel alloy, and two lots of heat-treated N-155 alloy. The alloy most resistant to thermal cracking was the Haynes-Stellite 21 alloy heat-treated for increased ductility. The unheat-treated Haynes-Stellite 21 alloy, Inconel, and the better lot of N-155

FIG. 15

VARIATION OF NUMBER OF CYCLES OF THERMAL SHOCK TO FAILURE WITH TEMPERATURE FOR SEVERAL ALLOYS.

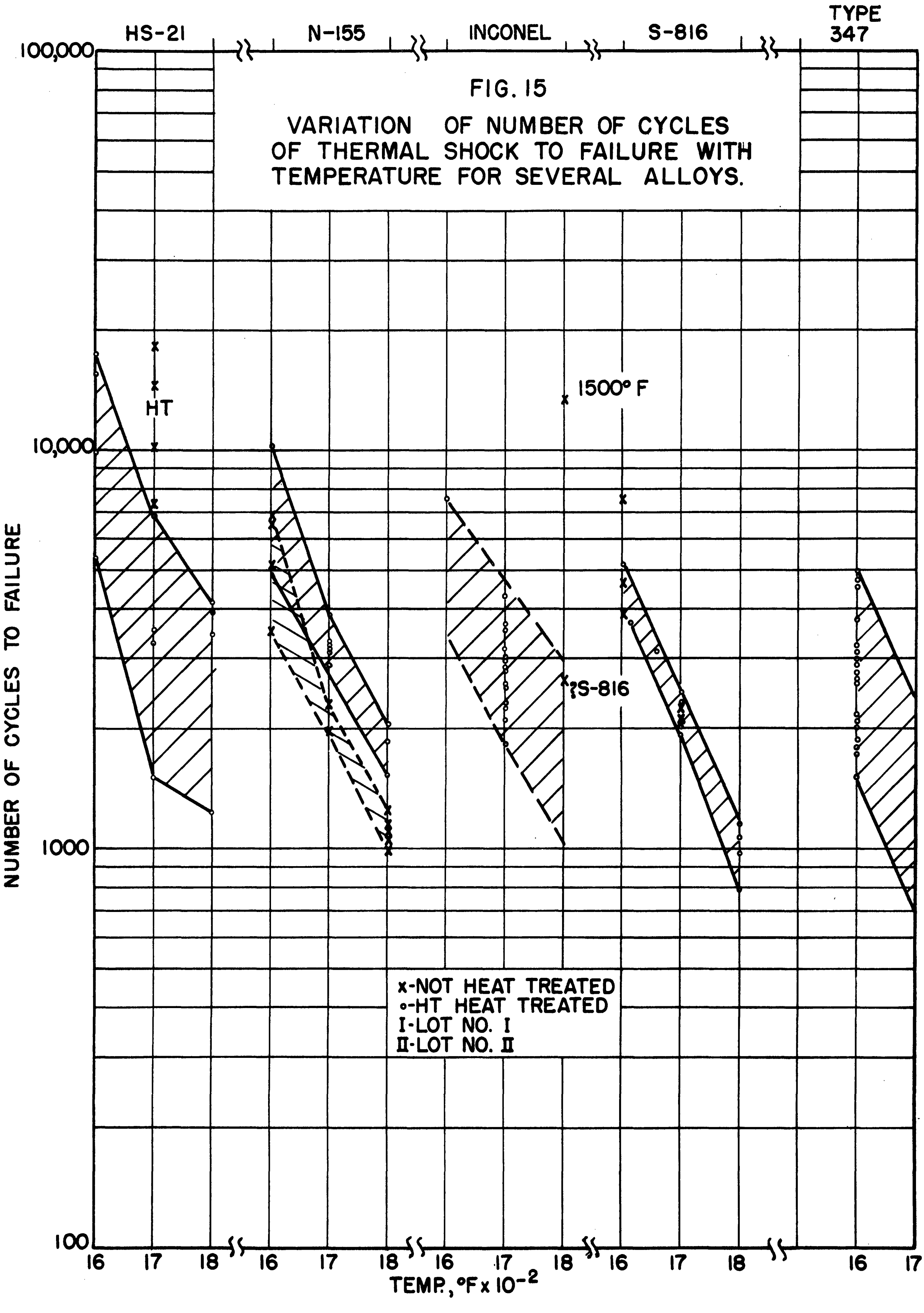
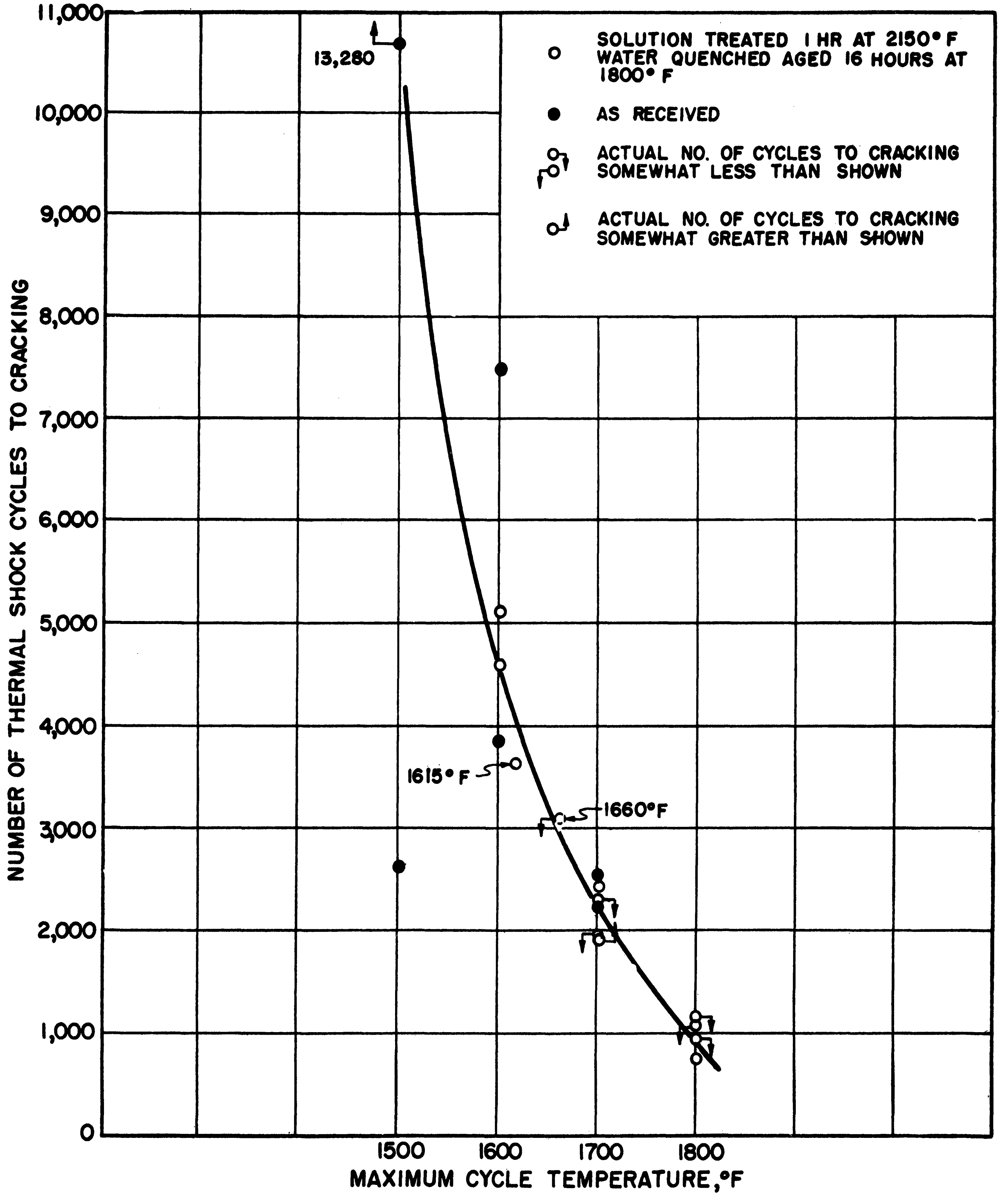


FIG. 16
S-816 ALLOY



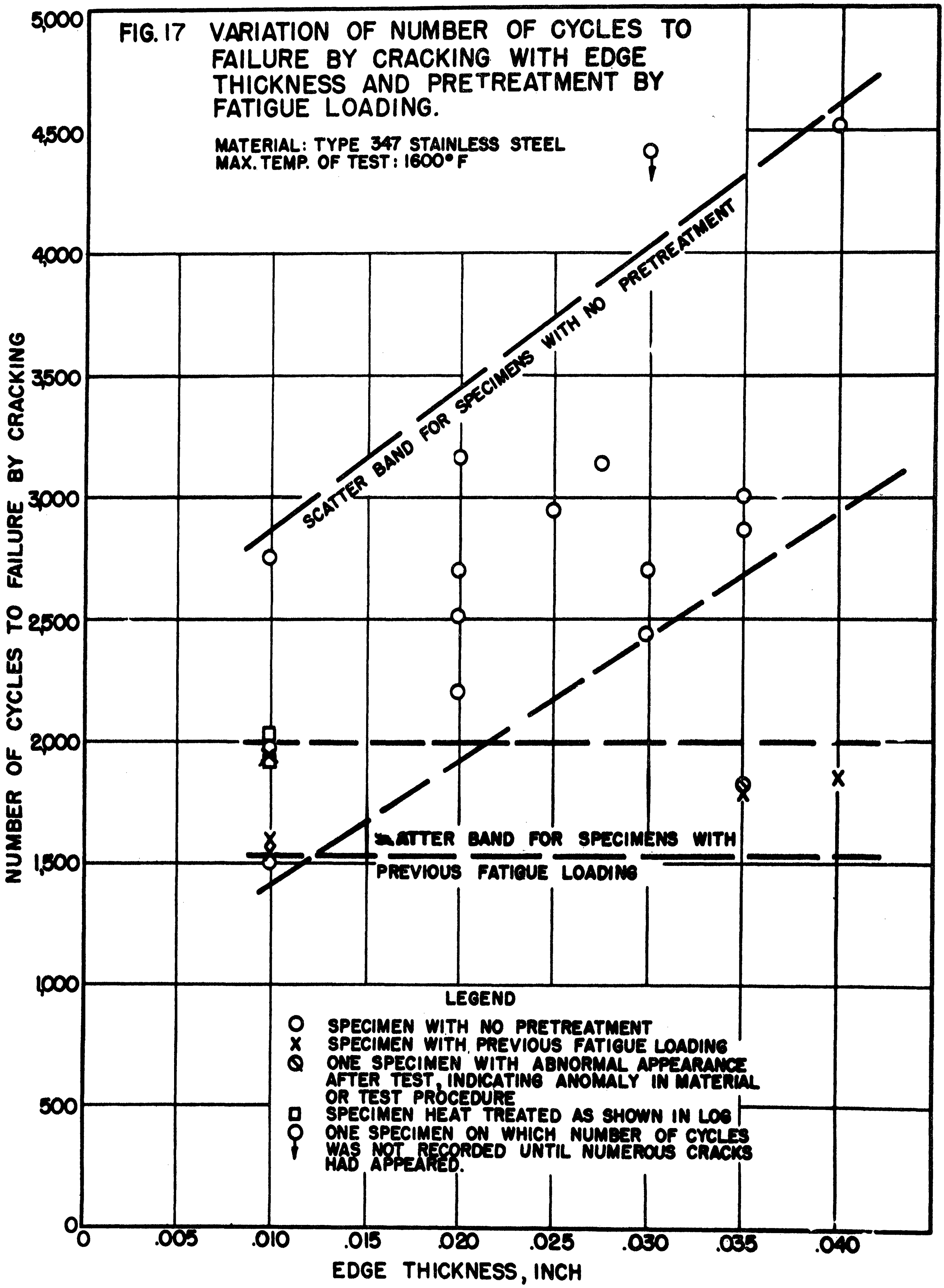


FIG. 17 VARIATION OF NUMBER OF CYCLES TO FAILURE BY CRACKING WITH EDGE THICKNESS AND PRETREATMENT BY FATIGUE LOADING.
MATERIAL: TYPE 347 STAINLESS STEEL
MAX. TEMP. OF TEST: 1600° F
SCATTER BAND FOR SPECIMENS WITH NO PRETREATMENT
SCATTER BAND FOR SPECIMENS WITH PREVIOUS FATIGUE LOADING
NUMBER OF CYCLES TO FAILURE BY CRACKING
5,000
4,500
4,000
3,500
3,000
2,500
2,000
1,500
1,000
500
0
0
.005
.010
.015
.020
.025
.030
.035
.040
EDGE THICKNESS, INCH
LEGEND
SPECIMEN WITH NO PRETREATMENT
SPECIMEN WITH PREVIOUS FATIGUE LOADING
ONE SPECIMEN WITH ABNORMAL APPEARANCE AFTER TEST, INDICATING ANOMALY IN MATERIAL OR TEST PROCEDURE
SPECIMEN HEAT TREATED AS SHOWN IN LOG
ONE SPECIMEN ON WHICH NUMBER OF CYCLES WAS NOT RECORDED UNTIL NUMEROUS CRACKS HAD APPEARED.

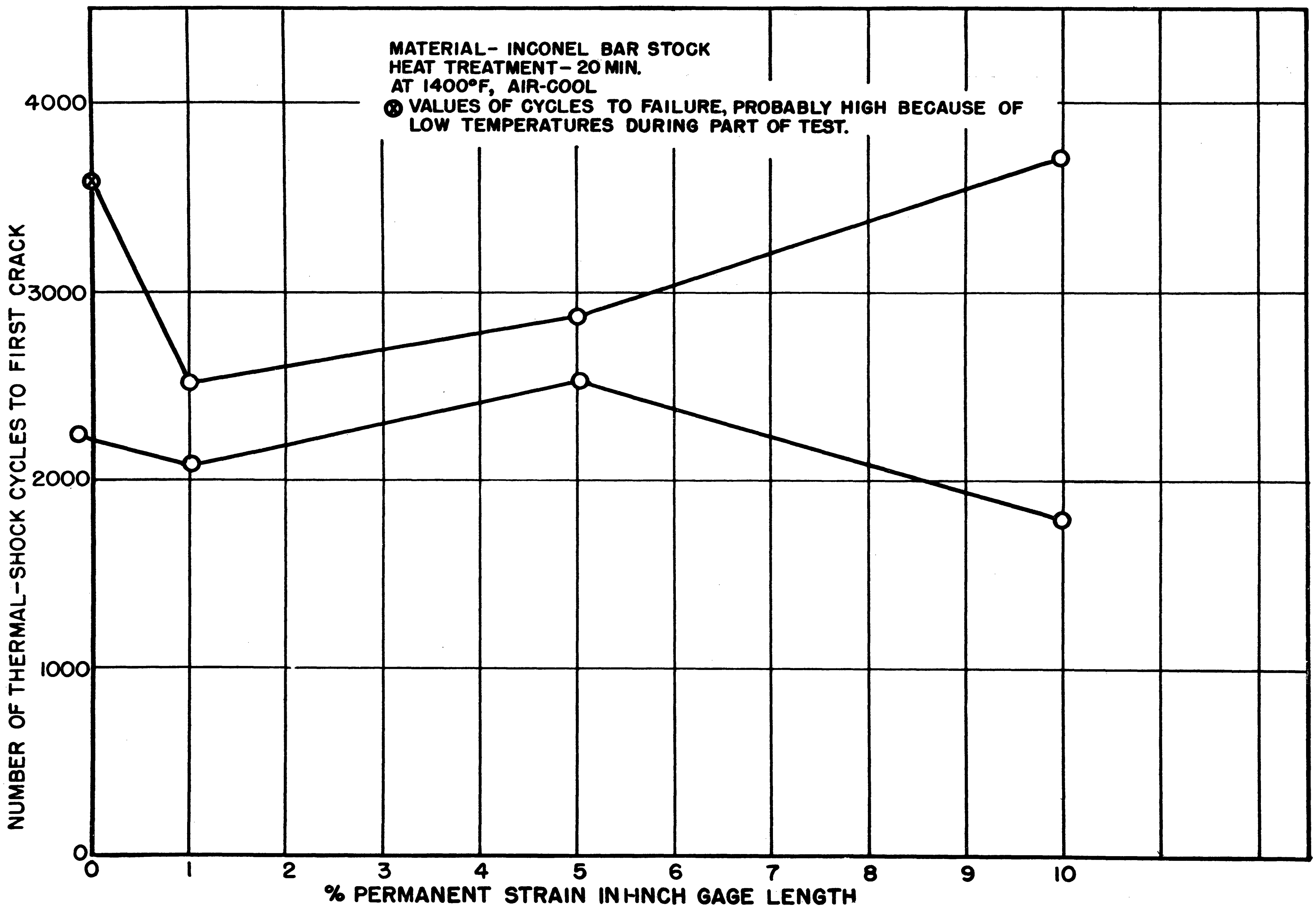

MATERIAL- INCONEL BAR STOCK
HEAT TREATMENT- 20 MIN.
AT 1400°F, AIR-COOL
⊗ VALUES OF CYCLES TO FAILURE, PROBABLY HIGH BECAUSE OF LOW TEMPERATURES DURING PART OF TEST.
NUMBER OF THERMAL-SHOCK CYCLES TO FIRST CRACK
4000
3000
2000
1000
0
0
1
2
3
4
5
6
7
8
9
10
% PERMANENT STRAIN IN 1-INCH GAGE LENGTH

FIG. 18

alloy were about equal in thermal-shock resistance. The poorest alloys were S-816 alloy and the poorer lot of N-155 alloy.

Tests at 1600°F indicated that the alloy most resistant to thermal cracking was Haynes-Stellite 21 alloy (no heat treatment was performed on the Haynes-Stellite 21 alloys tested at this temperature). The better lot of heat-treated N-155 alloy was about the same as the cast Haynes-Stellite 21 alloy just mentioned, but possibly slightly lower in resistance to cracking by thermal shock. S-816 alloy and the poorer lot of N-155 alloy were next best, and the poorest alloys of all, as might be expected, were the types 304 and 347 stainless steels.

2. Effect of Temperature

The effect of increasing the maximum cycle temperature is to decrease the number of thermal shocks required to produce cracking. This effect is graphically illustrated in Fig. 16, where the numbers of cycles to failure is plotted on a logarithmic scale versus temperature on a Cartesian scale. It is theoretically possible for the number of cycles required to produce cracking to rise at some elevated temperatures because of the increased ductility of the bulk metal at those temperatures, but such behavior was not encountered in these tests.

3. Effect of Prior Fatigue Damage

The tests conducted on type 347 stainless steel were performed on specimens in the as-received condition and after repeated stressing in a low-speed (1750-rpm) rotating-beam fatigue machine. The fatiguing was of such severity that about half the specimens so treated failed in the fatigue test. The results of thermal-shock tests are shown as a function of specimen edge width in Fig. 17. It can be seen that the fatiguing has made the specimen somewhat insensitive to edge width, whereas the as-received specimens increase in resistance to thermal shock as the edge width is increased. This variation of number of cycles to cracking with edge width did not hold as true with other alloys.

4. Variation of Thermal-Shock Resistance with Cold Work

A number of Inconel specimens were heat-treated as a lot, after which three each were stretched in a tensile machine to permanent strains of 1, 5, and 10%, and three were not stretched at all. There was no significant change in thermal-shock resistance with this cold work. See Fig. 18.

5. Reproducibility of Results

The tests run specifically on reproducibility were more closely controlled than other tests, particularly the earlier tests. The best reproducibility tests indicated a range of 15%. Other tests indicated a range of 20%. These ranges are the best that have been found, with earlier ranges of results much wider. Inasmuch as the range is affected by the material employed (constancy of physical properties in a given lot of material), the 15% value obtained for type 347 stainless steel will probably not be bettered by the high-temperature alloys, although S-816 yielded a range of 20%.

6. Effect of Miscellaneous Pretreatments on the Thermal-Shock Resistance of Alloys

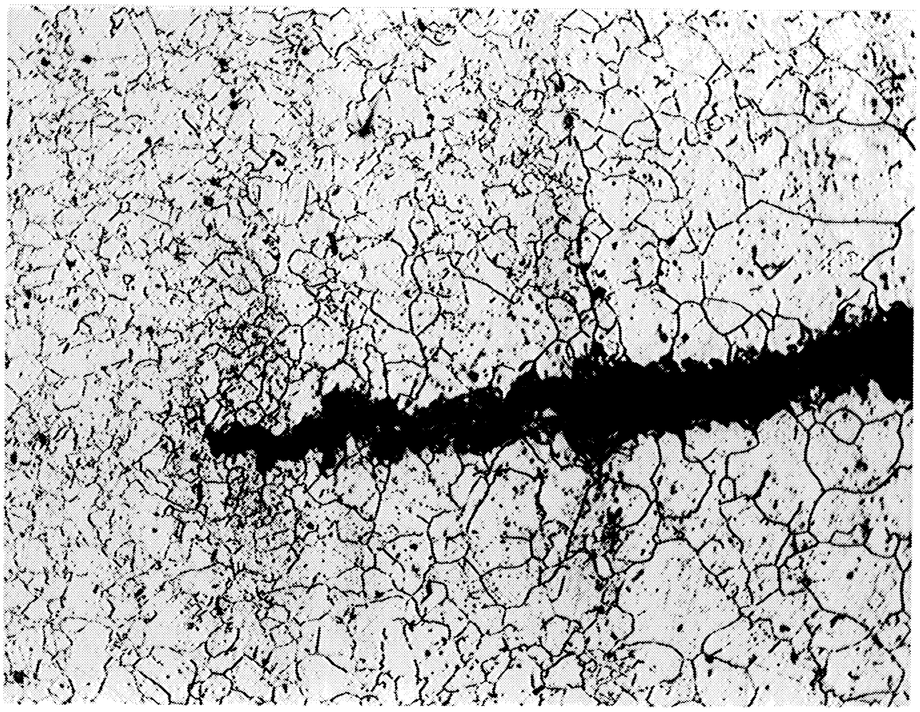
a) Three specimens of Inconel were given two-hour soaks at 500°F prior to the usual heat treatment of twenty minutes at 1400°F. The results of these tests had the widest spread obtained with any single lot of specimens, with two of the three specimens in the lot yielding respectively the highest and lowest numbers of cycles to failure at 1700°F for Inconel.

b) One specimen of Inconel was subjected to heating to 1700°F in about one minute, followed by natural convection cooling for five seconds, all for a period of twenty hours. This specimen yielded one of the lowest numbers of cycles to fracture obtained for Inconel in the 1700°F tests.

c) Tests of lowered severity of air blast resulted in increased numbers of cycles to failure on two Inconel specimens. Photomicrographs indicated that there were no apparent differences in the cracks. The cracks were intercrystalline rather than transcrystalline, and showed severe damage. See Figs. 19-23.

7. Type of Crack Produced by Thermal Shock

The study of microstructures in the environs of the cracks is not yet complete. Tentative results are that the crack tends to propagate between the grain boundaries as shown in Fig. 20, but that subsequent oxidation and plastic deformation obscures the early region of the crack, tending to make it appear as though transcrystalline. The general path of the crack in a small-grained material would thus appear to be straight (perpendicular to the direction of the thermal stress), although it may well be intercrystalline. More study is required on this point.



Cooled
Edge

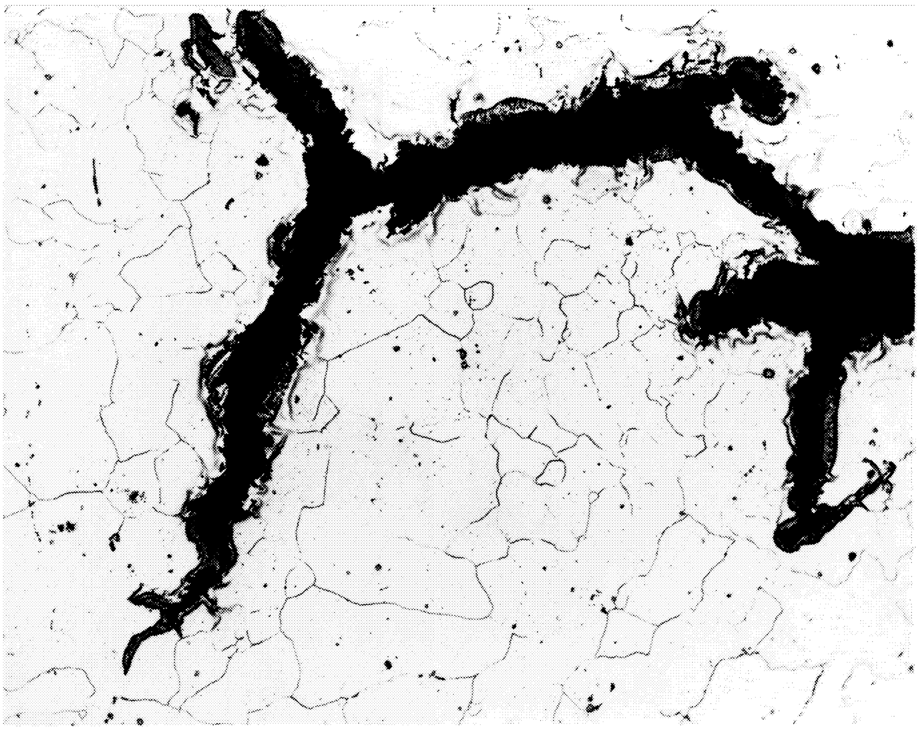
Fig. 19. IN-5, 1819 Cycles, 100X

Standard Shock

Cooled
Edge

Fig. 20. IN-7, 4706 Cycles, 100X

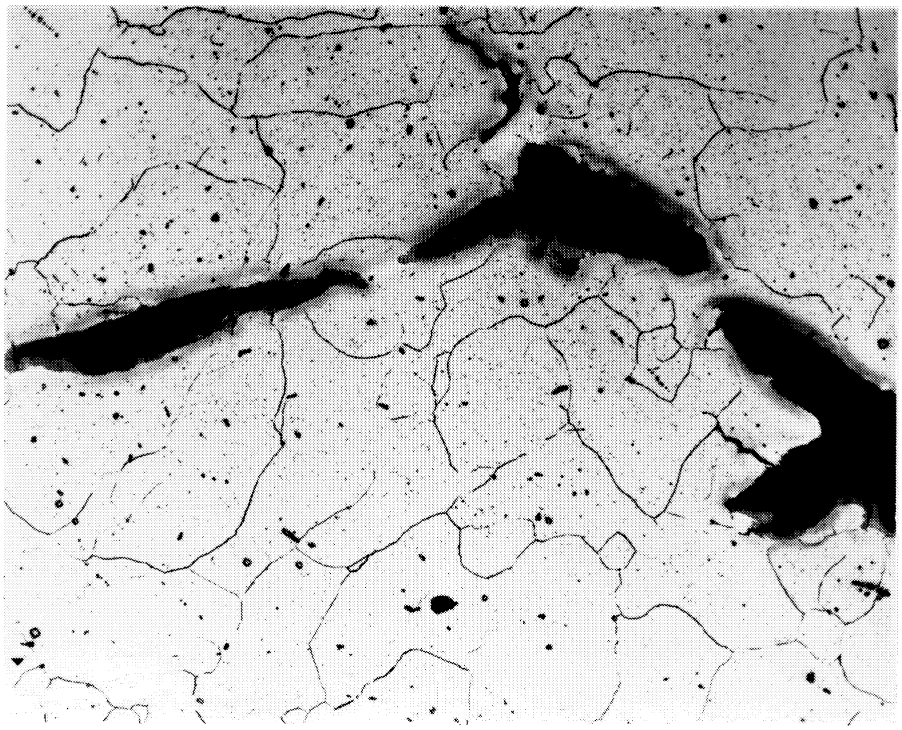
Standard Shock



Cooled
Edge

Fig. 21. IN-21, 11,265 Cycles, 100X

Reduced Shock



Cooled
Edge

Fig. 22. IN-24, 8145 Cycles, 100X

Reduced Shock

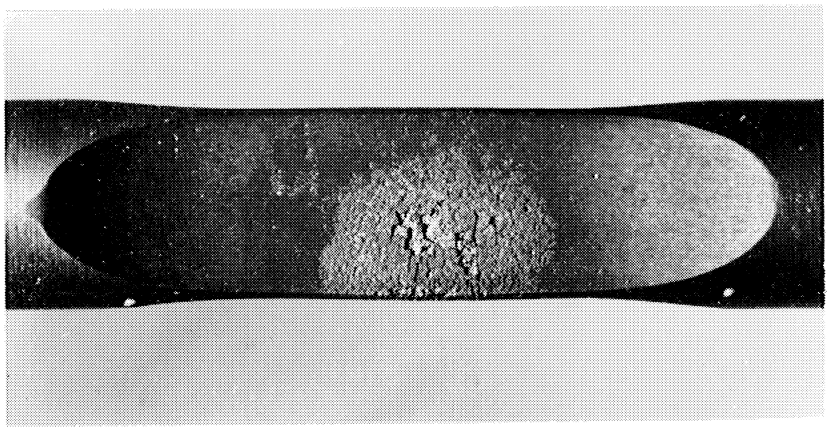


Fig. 23. IN-21, Showing Severe Corrosion on Surface, 11,265 Cycles

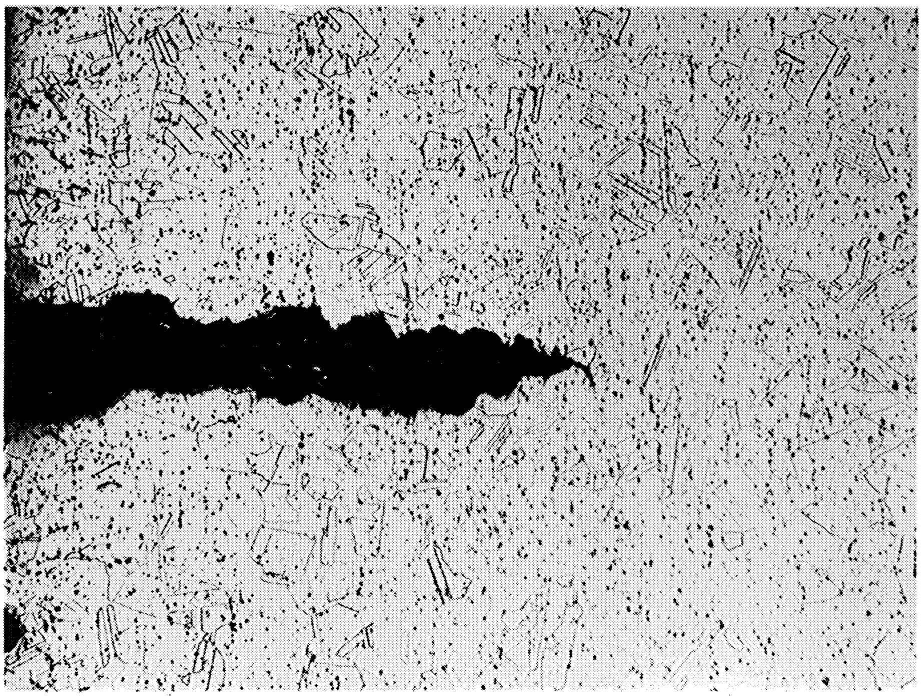


Fig. 24. Thermal Crack in Type 304 Stainless Steel
100X

CONCLUSIONS

1. For usual metallic alloys intended for high-temperature uses, a single thermal shock is insufficient to produce cracking except for shapes of greatly varying section, or for severity of shock so great that the rate of loading affects material properties.

2. It is probable that exposure to high temperature and/or stress causes deterioration of alloys until a single thermal shock suffices to produce a crack.

3. In tests of high-temperature alloys subjected to repeated thermal shocks from temperatures of 1600 to 1800°F, the order of decreasing resistance to thermal shock was Haynes-Stellite 21 cast, Inconel, N-155, and S-816 alloy. Stainless steels of types 321 and 347 were poorer than the high-temperature alloys.

4. Previous fatigue damage, short of visible cracking, reduced the thermal-shock resistance of type 347 stainless steel.

5. Lowered severities of thermal shock increased the number of thermal-shock cycles to failure.

6. Specimens of Haynes-Stellite 21 cast alloy manifested improved thermal-shock resistance when heat-treated to increase ductility as measured in room-temperature tensile tests.

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