THERMAL SHOCK:
AN ANNOTATED BIBLIOGRAPHY

SPECIAL BIBLIOGRAPHY
SB-62-39

SEPTEMBER 1962
THERMAL SHOCK:
AN ANNOTATED BIBLIOGRAPHY

Compiled by
SCOTT J. BUGINAS

SEPTEMBER 1962

Lockheed
MISSILES & SPACE COMPANY
A GROUP DIVISION OF LOCKHEED AIRCRAFT CORPORATION
SUNNYVALE, CALIFORNIA
ABSTRACT

The search made began with the literature of 1956. Glenny (24) in 1961 and Majors (29) in 1957 have written extensive review articles concerning thermal fatigue. Some of the references in these articles apply directly or are related to the subject of this bibliography.

This search was oriented toward aiding LMSC researchers in developing a definition for thermal shock (there are conflicts in the literature) and in studying thermal shock vs. fatigue cycling.

Search completed August 1962.
Availability notices and procurement instructions following the citations are direct quotations of such instructions appearing in the source material announcing that report. The compiler is well aware that many of these agencies' names, addresses and office codes will have changed; however, no attempt has been made to update each of these notices individually.

In citing classified reports, (SECRET TITLE) or (CONFIDENTIAL TITLE) as appropriate, has been used when that classification of the title was indicated on the report. (UNVERIFIED TITLE) has been used when the report was not available to the compiler and it was impossible to verify the report's title and the title's security level.

Classification of classified reports is indicated by abbreviation in upper right top line of bibliographic entry. The classification of the report is given in full, e.g., SECRET REPORT, at the conclusion of the bibliographic data for that report entry.

This selective bibliography has been prepared in response to a specific request and is confined to the limits of that request. No claim is made that this is an exhaustive or critical compilation. The inclusion of any reference to material is not to be construed as an endorsement of the information contained in that material.
1. Bal’shin, M. Yu. and Huei, T.S.
CERTAIN PROBLEMS OF THERMAL
STABILITY. Foreign Tech. Div., Air Force
Systems Command, Wright-Patterson Air
Force Base, Ohio. 3 Nov 1961, 9p. ASTIA
AD-266 760. (Trans. no. FTD-TT-61-160 of
IZVEST. AKAD. NAUK S.S.R., OTDEL,
TEK. NAUK, MET. i TOP. v. 3, p. 73-76,
1961.)

The mechanism of the phenomena which arise in a solid as a result of cyclic heat
treatment with rapid changes in temperature was studied. The conductivity of graphite
with and without impregnated bakelite was measured to evaluate the thermal stability
of the materials during heat treatment. It was confirmed experimentally that during
cyclic heat treatment, the internal stresses associated with temperature variations
caused a decrease in the contact surface. Compressive stresses associated with mi-
ute cavities in solids containing dispersed particles decreased electrical resistance
and increased the contact surface. The thermal stability of a solid is determined by
the properties, size, and shape of the material. Surface films can increase the ther-
mal stability of a solid.

2. Baron, H.C. and Bloomfield, B.S.
RESISTANCE TO THERMAL FATIGUE
CRACKING OF SEVERAL TYPES OF CAST
IRON. Armament Research and Development
Establishment (Gt. Brit.). ARDE Memo. no.

Cracking was produced in test pieces of chilled white iron, engineering grey iron and
two casts of nodular iron, by repeated heating of one edge of the specimen while the
mass of the specimen was water cooled. The white iron gave extensive cracks when
heated to 650°C, but survived several thousand cycles of 40 - 450°C due to its high
compressive strength. The grey iron gave a fatigue curve lying between the white
2. (cont'd) and nodular irons over much of the temperature range, but with the low temperature cycle of 40 – 500°C it showed greater resistance to cracking than the nodular irons. This unexpected result is attributed to the low elastic modulus of grey iron. The nodular irons were comparable with plain carbon steels in their resistance to cracking. In low temperature tests they were slightly more resistant to cracking in the as-cast state than after annealing to produce a ferrite matrix. With cycles at 40 to 850°C or to 1000°C the annealed material was better.

3. Bollenrath, F.

Study of the thermal shock problem in aircraft structures. The case of a plate between two high-speed flows (one hot, one cold gas) is considered. Pressure distribution dependent on time and plate thickness is calculated for various structural materials.

4. Bollenrath, F.
SOME REMARKS UPON THE PROBLEM OF TEMPERATURE SHOCK IN AIRCRAFT. AGARD rept. no. 90, Aug 1956, 12p.

Structural problems, particularly thermal shock, associated with nonuniform, transient temperatures in structural members are discussed in general. The temperature distribution in a thick plate heated on one surface and cooled on the other by forced convection is calculated and resulting thermal stresses are determined for two types of restraint.


Includes basic theory with mechanical and thermodynamic foundations. Heat conduction and thermal stress analysis are discussed for elastic and inelastic systems.

LOCKHEED MISSILES & SPACE COMPANY
6. Clauss, F.J. and Freeman, J.W.

THERMAL FATIGUE OF DUCTILE MATERIALS.


The experimental results indicated that the maximum cycle temperature had more effect than the temperature difference on the number of cycles to failure. Increasing the cycle time of exposure at the maximum cycle temperature improved the thermal-fatigue life at high maximum cycle temperatures, whereas the same increase in exposure time at low maximum cycle temperatures decreased the number of cycles to failure. The number of cycles to failure depends upon temperature and time effects in addition to the thermal strains absorbed by plastic flow.

7. Clauss, F.J.


Describes a fundamental study of thermal fatigue in ductile alloys. The effects of cyclic temperature variables on thermal fatigue are discussed. The extent of changes in the stress-rupture strength and ductility caused by varying amounts and conditions of thermal fatigue prior to fracture is evaluated. Experimental observations on thermal fatigue behavior are explained on the basis of present theories of the solid state.
8. Clements, J. F. and Vyse, J.

The response of fireclay products to thermal shock can be separated into the following properties: a tendency to crack during heating or cooling, and a tendency to break after cracking.


The author reviews thermal-stress effects observed in ductile metals and describes experiments in which parameters of thermal-stress fatigue arising from the constraint of thermal expansion were determined. Results for the effects of the temperature range, cold working, mean temperature, and speed of cycling on thermal-stress fatigue are given. The significance of the plastic-strain range and its relation to cycles to failure is discussed.

Thermal stress fatigue. PROD. ENG.

v. 28, p. 175-179, June 1957.

Discusses the differences between mechanical and thermal fatigue, the origin of thermal stresses, the role of thermal cycling in fatigue, and defines thermal shock parameters.


In the past, vehicles operated in a fairly low temperature environment. The selection of materials were primarily dependent on the quasi-static and dynamic loads. With the advent of manned hypersonic glide re-entry vehicles, the temperature and time parameters were found to significantly affect the selection of materials. In this report the criteria for including the effects of temperature and time are clarified by using six measuring sticks. Two materials, Inconel 718 and Haynes 25 were evaluated for repeated exposure to a typical hypersonic re-entry glide trajectory.

13. Delmas, R.

13. (cont'd) The test consisted of heating the trailing edge of nozzles with controlled propane flame and then cooling with an air blast. The temperature cycling range was from 250 to 1150°C; heating and cooling times were 55 and 26 secs, respectively. The materials investigated were gas turbine metallic alloys and cermets. Elastic analyses of stresses for both temperature gradient through thickness and along length of nozzle were made on basis of flat plate.

14. DeVries, D.

How corn products licked thermal shock problem.


Ambient air at 90°F and combustion gases at 1600°F caused thermal shock, stress cracking and high temperature corrosion in a flash dryer used for processing grain sorghums into several products. Hastelloy X was used to overcome the problems and resulted in excellent strength and corrosion resistance.

15. Dolan, T.J.


Contains a summary of the findings of ASTM Research Subcommittee of Committee E-9 on fatigue. The extent of present knowledge is outlined and different types of basic research are discussed. Recommendations for concentrated research efforts are included.

16. Dugdale, R.A.

THERMAL-SHOCK AND THERMAL-STRESS FATIGUE IN A STABILIZED PINCH-FUSION REACTOR. U.K. Atomic Energy Authority

Publ. no. R.2955, 1959, 14p.

An estimate of the temperature difference developed across the reaction-chamber wall and the resultant stresses and strains set up is used to predict conditions which would produce cracking of the wall.
17. François, M.


Non-cyclic study. The refractory face is heated with a standard gas flame. Cracks are observed as they occur during cooling.


A theoretical discussion of fatigue phenomena is presented and a mechanism of fatigue-crack initiation within glide bands is expounded. The highly localized temperature and associated thermal-stress gradients in front of active slip-planes are postulated to be sufficiently severe to account for the initiation of micro-cracks parallel to the slip planes, provided that slip under repeated stress is concentrated into striations. The concept avoids difficulties associated with earlier theories of strain-hardening. The effect of the thermal characteristics of a metal on its fatigue performance is discussed with particular reference to commercially pure Al and Al alloy 24S-T.

19. Gatewood, B.E.


Includes some information on thermal shock.

20. Gilbey, D.M.


Discusses an extension of the theory of thermal stresses which allows the "constants" of thermal conductivity, thermal expansion, Young's modulus, and Poisson's ratio to vary with temperature. The data needed include sufficient stress/strain curves at different temperatures and the variation of thermal conductivity and thermal expansion with temperatures. Thermal stress calculations are programmed for a computer.
21. Glenny, E.


Defines various aspects of the problem, and concludes that the primary causes of failure are due to cyclic strain fatigue, cyclic creep or corrosion-fatigue. Each application must be given individual treatment. The increasing complexity of service conditions has brought about a need for closely simulative testing. 170 references are included.

22. Glenny, E. and Royston, M.G.


Investigation of the validity of the theory for calculating transient thermal stresses. A high alumina ceramic is tested with hot and cold fluidized beds as heating and cooling media. The agreement between experiment and theory is reasonable considering the nonstatistical nature of the experiments and the assumptions involved in developing and using the theory, as well as in correlating the thermal stress to failure with breaking strength.


A technique for thermal-shock and thermal-fatigue testing based on the use of fluidized solids.


Describes laboratory tests for studying the behavior of materials under conditions of transient thermal stress such as might arise in gas turbine blades. The specimen is immersed in a bed of powered refractory substance supported on a permeable plate and fluidized by a stream of air.
24. Hetnarski, R.


A generalized heat equation coupled with elastic deformation is presented. The equation must be considered only for dynamic problems because in a static case, the coupling effect vanishes.

25. Hillier, M.J.

Correlation of thermal stresses in circular cylinders and flat plates. ENGINEER v. 207, n. 5372, p. 56-57, 1959.

Published data concerning the production of a stress system within hollow cylinders, which are lagged on the inner face because of a steep change in fluid temperature adjacent the metal surface, are reworked on a common base and compared.

26. Hoff, N.J. (ed.)


Contains 16 summaries of fields which enter into the analysis of thermal problems arising from aerodynamic heating. Information on high temperature fatigue and thermal stresses is included.

27. Kennedy, C.R.

Plastic strain absorption as a criterion for high temperature design. In FOURTH SAGAMORE RESEARCH CONFERENCE ON HIGH TEMPERATURE MATERIALS, THEIR STRENGTH POTENTIALS AND

The development of isothermal strain reversal data as an aid to high temperature design is proposed. A test apparatus capable of mechanically cycling a specimen in tension and compression within set strain limits is described. Data are presented which confirm Coffin's theory that total plastic strain per cycle can be used to predict the number of cycles to failure. Evidence that Inconel strain weakens at the test temperature is noted and grain size is found to be the most important variable affecting the behavior of materials subjected to strain reversals.

28. King, D.F. and Walther, F.H.


The furnace is equipped with automatic motor-driven rotation, is gas fired with open air cooling, and operates easily on a 2400-1000°F cycle. Tests on a wide range of refractory materials showed much variation in their ability to resist thermal shock.

29. Kostochkin, Yu. V. and Oding, I.A.


Experiments were carried out on a Ni-Cr alloy EI-765 and an austenitic steel EI-612 used for gas-turbine blades. Samples were heated in a current of hot gas at 750°C and cooled to 70°C to simulate actual working conditions. Tests for creep resistance were made. An increase in the number of thermal cycles resulted in a shorter life on test. The rate of reduction in life was retarded with an increase in the number of cycles. Final fracture occurred when the crack was half way across the specimen, by transcrysalline cracking as in a tensile test. The failure of a specimen not
29. (cont'd) subjected to thermal cycling occurred simultaneously across the entire section by intercrystalline cracking. Micro-damage caused by thermal cycling has little effect in a tensile test but develops into macro-cracks during creep testing. Creep testing is, therefore, a convenient method of showing up the damage caused by thermal cycling.

30. Lauchner, J.H. and Bennett, D.G.


Four cobalt-bearing ground-coat type coatings applied to enameling grade iron specimens were studied. Indications were that after receiving a given thermal treatment, ceramic coatings fracture when subjected to thermal shock by a critical temperature differential. Residual compressive stress in a coating is a major factor in improved thermal shock resistance. Increased resistance to thermal shock is gained by decreasing coating thickness.


Cooling rates affect development of thermal stresses. Residual compressive stresses in enamel are increased by rapid cooling from firing temperatures.

32. Laval, J.


Thermal stresses as a function of temperature are estimated. At low and intermediate temperatures, they are directly proportional to the square of the average quadratic amplitudes of the fundamental thermal oscillations.
33. Lazarev, G. P.

34. Lessen, M.

The problem of "initial" thermal shock is formulated and the solution is found to be similar to that of a Fourier equation with modified diffusivity.

35. L'vovskii, M. Ia. and Smiian, I. A.

The authors give a brief account of the technique for measuring the comparative resistance of sheet materials to thermal shock. The specimen is in the form of narrow tapered strip 185 mm long with an accurate notch cut in center of wider end (20 mm wide). Equipment is provided to automatically retain the strip in an electric furnace until the temperature at the notched end (recorded by thermocouple on specimen) reaches a preset value. Strip then is dropped by the solenoid into a quench bath and the cycle repeated. Cycle time is approximately 1 min and 5 sec. End point of the test is when a crack spreading from the notch measures a fixed length. The apparatus is designed for metal testing.


The relative thermal shock resistance in air, under stress, of eight protective coatings were evaluated. The temperature cycle used was 1800°F to 200°F and the stress was 45,000 psi. Specimens were tested until failure or 500 cycles occurred. Specimens which performed well during the 1800°F to 200°F cycle were tested using a 2000°F to 300°F cycle.

37. Majors., H., Jr.


Contains 45 references. Among the conclusions drawn were the following: In order to attempt a correlation of load cycling with thermal fatigue cycling, more data are needed for several mean temperatures; thermal cycling had a tendency to smooth the grain boundaries, thermal cycling under constant load displayed heavy inter-granular oxidation on the inner surfaces of the tubular specimens, and there was no influence on the coefficient of thermal expansion with cycles of thermal cycling under constant load.

38. Manson, S.S.


LOCKHEED MISSILES & SPACE COMPANY
38. (cont'd) Discusses thermal shock in flat plates, quantitative determination of thermal shock parameters experimentally and thermal stress fatigue.

39. Manson, S.S. and Smith, R.W.,
Quantitative evaluation of thermal-shock resistance.
TRANS. AM. SOC. MECH. ENGRS,
v. 78, n. 3, p. 533-544, Apr 1956.
Thermal shock resistance is dependent on two parameters: conductivity and the ratio of fracture stress to the product of the elastic modulus and the coefficient of thermal expansion.

40. Marin, J. (ed.)
MATERIALS ENGINEERING DESIGN FOR HIGH TEMPERATURES. Pennsylvania State University.
A short course was held with the objective of presenting current knowledge on the response of materials to elevated temperatures and how it can be applied to high temperature design. The problem of cyclic temperature fatigue is handled by Coffin in Chapter V which contains a discussion of current research on thermal fatigue. A method for conducting thermal fatigue studies is illustrated. The author shows the influence of prior cold work, stress and strain cycling, change in stress range, mean temperature, speed of cycling, plastic strain range, and in-phase relations between temperature and strain cycling, upon thermal fatigue. Extensive constant-temperature strain cycling tests were conducted because of the complex cyclic temperature tests. Other factors related to strain cycling are included, viz. strain localizing, cyclic strain-induced creep, and applications to design.

41. Meker, G.
Includes test data.

LOCKHEED MISSILES & SPACE COMPANY
42. Mendelson, A. and Manson, S.S.
Approximate solution to thermal-shock problems
in plates, hollow spheres and cylinders with heat
transfer at two surfaces. TRANS. AM. SOC.
MECH. ENGS., v. 78, n. 3, p. 545-553,
Apr 1956.

Transient thermal stresses are computed using a method which applies polynomial
approximations to temperature distribution to a reduced partial differential equation
of the problem to a set of first order ordinary differential equations.

43. Miller, D.R.
BIBLIOGRAPHY ON THERMAL STRESSES AND
LOW CYCLE FATIGUE. Knolls Atomic Power
Lab. Rept. no. KAPL 2048, 20 Aug 1959, 29p.
200 references.

44. Nariboli, G.A.
Spherically symmetric thermal shock in medium
with thermal and elastic deformations coupled.
QUART. J. MECH. AND APPL. MATH.

Discusses the effect of thermoelastic coupling on the passage of a disturbance through
an infinite medium with spherical cavity when its temperature is suddenly changed.
The effect of coupling is to reduce the fluctuation of stress and the "shock" character
of the disturbance.

45. Parkes, E.W.
A DESIGN PHILOSOPHY FOR REPEATED
THERMAL LOADING. Advisory Group for

LOCKHEED MISSILES & SPACE COMPANY
Presented at the Eighth Meeting of the Structures and Materials Panel, held 20-25 Oct 58, in Copenhagen, Denmark. The problem of the stress associated with change of temperature occurs in civil and mechanical engineering and is there almost invariably overcome by permitting free thermal expansion. The idea of free thermal expansion can sometimes be applied in the newer branches of engineering, but in many cases this is not so — the thermal strains are resisted and thermal stresses result. The magnitude of these thermal stresses can be reduced by the use of insulation, or by combining materials having different properties, but even with these aids the stresses are likely to exceed the limit of elasticity of the material for quite small temperature changes. It follows that if full use is to be made of the high temperature materials we must design inelastically. Designing inelastically for one cycle of thermal loading is comparatively easy, but if the thermal loading is repeated a number of times, the structure may suffer from alternate plasticity (and possible strain fatigue) or from incremental collapse. The use of a safety factor applied to the stresses is unduly conservative, whereas the use of a safety factor applied to the loads may be dangerous. It is possible that the concept of a statistical safe time for the structure, based upon its expected load-temperature-time history, may have to be used. These various aspects of the problem are discussed in this report and illustrated with calculations for some simple models in which the load is kept constant and the temperature varied cyclically.

Pridantsev, V. M. and Krylova, A. R.
A method of determining the resistance to thermal shock of sheet steels and alloys.

An apparatus is described for thermally cycling a sheet specimen having an arbitrary size and configuration of holes and for measuring the number of heating and cooling cycles required to produce the first crack. This comparative test does not yield basic material properties. Tests on austenitic Cr-Ni steel indicate that the logarithm of the cycles to first crack decreases with an increase in temperature amplitude. Cycles to thermal fatigue failure also decrease as sheet thickness increases and grain size decreases.
47. Royston, M.G.


It is possible to explain quantitatively the variation of strength of brittle materials with size and mode of stressing. By an extension of Weibull's theory (AD-76 790) a relation between bend strength and thermal fracture stress can be developed which permits the design of bend strength specimens that fail under conditions analogous to those of thermal shock.

48. Sadowsky, M.A.


 Discusses a case in which part of a plane surface of a body is exposed to spontaneous radiation causing a finite amount of heat to become absorbed by the exposed part of the surface.

49. Serensen, S.V. and Kotov, P.I.

Methods of recording cyclically changing temperatures and stresses in thermal fatigue tests. ZAVOD LAB., S.S.S.R. v. 27, n. 8, p. 1013-1018, 1961. (In Russian)
Tests with cyclic thermal stresses of varying severity in the investigation of thermal fatigue.

Effect of thermal stresses on the short-time, long-time and vibration strength of alloys.
SYMPOSIUM: ISSLED. PO ZHAROPR. SPLAV., MOSCOW, AKAD. NAUK SSSR v. 5, p. 39-41, 1959. (In Russian)

The effect of thermal stresses on short-time fracture, long-time tensile strength and fatigue strength was investigated. It has been established that, depending on the magnitude of the temperature drop and the mean temperature of the cycle, the number of cycles before fracture varies from a few cycles to $10^4$ plus cycles. No single-valued relation between the heat resistance and the plasticity of the materials was detected.

52. Sternberg, E. and Chakravorty, J.G.
THERMAL SHOCK IN AN ELASTIC BODY WITH A SPHERICAL CAVITY. Brown Univ., Div. of Applied Mathematics, Providence, R.I. Technical rept. no. 3, June 1958, 27p. (Contract Nonr-56225)
ASTIA AD-200 018.

This investigation aims at the dynamic thermoelastic response of an infinite medium with a spherical cavity to a sudden uniform change in the temperature of its internal boundary. By means of the Laplace transform, a closed solution to this problem - exact within classical elastokinetics - is obtained in terms of error functions of real and complex arguments. The ensuing temperature stresses are compared with the corresponding quasi-static results.
53. 

Sternberg, E. and Chakravorty, J.G.
Thermal shock in an elastic body with a spherical cavity. QUART. APPL. MATH.

The elastic response of an infinite medium containing a spherical cavity is analyzed for the case of an instantaneously applied uniform temperature change at the cavity wall. Numerical results show a pronounced oscillation of dynamic stresses at the inner boundary, and a propagating shock wave elsewhere, with a decreasing jump discontinuity as the wave-front progresses away from the cavity.

54. 

Weiss, V., et al

The effect of thermal cycling under constant stress on 7075-T6 and X2020-T6 Al alloys and AZ31B-H24 and Hk31A-H24 Mg alloys was investigated for sawtooth type cycling between -320°F. and maximum temperatures of 600°F. for the Al alloys and 400°F. for the Mg alloys.

55. 

White, J.
Some general considerations on thermal shock.

Two quantitative theories of brittle fracture are reviewed. The first assumes a brittle material remains elastic up to the point of fracture. In the second, a probability of fracture is assumed which depends on the volume of material stressed and the probability of Griffith cracks being activated. A theory of thermal shock in a two-phase
55. (cont'd) material is developed in which thermal stress is defined as a function of the expansion coefficient. Thermal stresses arising from anisotropy, and suggested explanations of expansion hysteresis are discussed also.

56. Yen, T.C.


Literature survey. Includes data on test procedures and fatigue life and stress rupture for experiments with 304 Stainless, Inconel 550, A302 steel and S-816 alloys at temperatures up to 1600°F.