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BITHERMAL FATIGUE: A SIMPLIFIED ALTERNATIVE TO THERMOMECHANICAL FATIGUE

Michael J. Verrilli
Fatigue and Fracture Branch
NASA Lewis Research Center

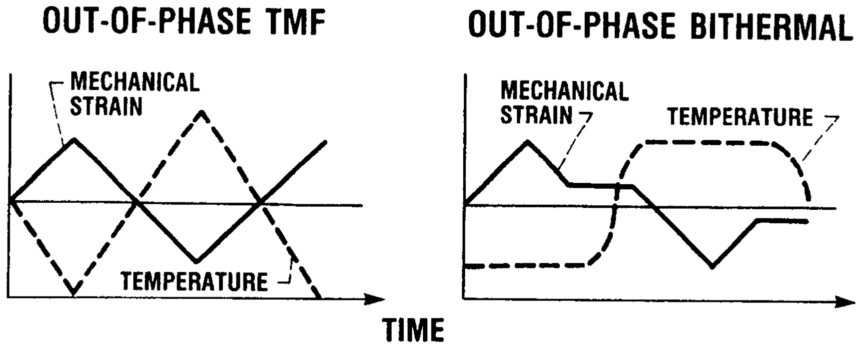
ABSTRACT

A bithermal fatigue test technique has been proposed as a simplified alternative to the thermomechanical fatigue test. Both the thermomechanical cycle and the bithermal technique can be used to study nonisothermal fatigue behavior. The difference between the two cycles is that in a conventional thermomechanical fatigue cycle the temperature is continuously varied concurrently with the applied mechanical strains, but in the bithermal fatigue cycle the specimen is held at zero load during the temperature excursions and all the loads are applied at the two extreme temperatures of the cycle. Experimentally, the bithermal fatigue test technique offers advantages such as ease in synchronizing the temperature and mechanical strain waveforms, in minimizing temperature gradients in the specimen gauge length, and in reducing and interpreting data. In addition, the bithermal cycle captures first-order effects of nonisothermal fatigue such as the influence of alternate high and low temperatures on the cyclic stress-strain response characteristics, the effects of thermal free-expansion mismatch straining between the oxide (or coating) and the substrate, and the possibility of introducing high- and low-temperature deformation mechanisms within the same cycle. The bithermal technique has been used to study nonisothermal fatigue behavior of alloys such as single-crystal PWA 1480 (Gayda et al., 1987), single-crystal René N4, cast B1900+Hf (Halford et al., 1988a), and wrought Haynes 188 (Halford et al., 1988b).

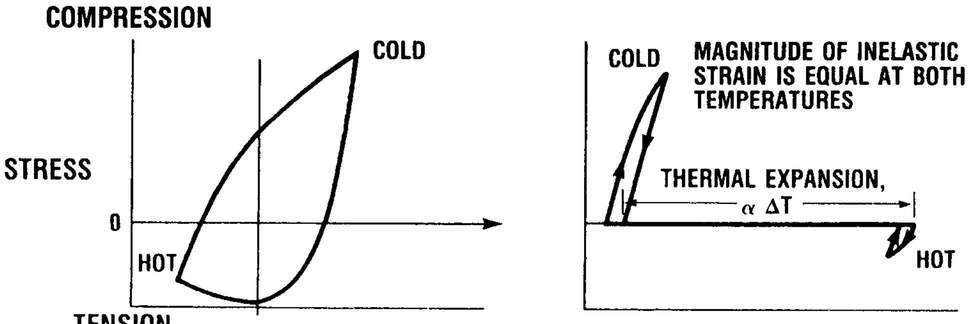
OVERVIEW

BITHERMAL VERSUS TMF

In studying TMF the bithermal cycle is a simplified alternative to the more conventional continuously varying temperature TMF cycle. Pictured below are an out-of-phase bithermal cycle and an out-of-phase TMF cycle. In an out-of-phase cycle the tensile mechanical strain is imposed at the low temperature. In the bithermal cycle the mechanical strain excursions and the temperature excursions are decoupled, whereas in the TMF cycle both temperature and mechanical strains are cycled simultaneously.



TEMPERATURE AND STRAIN WAVEFORMS



THERMAL PLUS MECHANICAL STRAIN HYSTERESIS LOOPS

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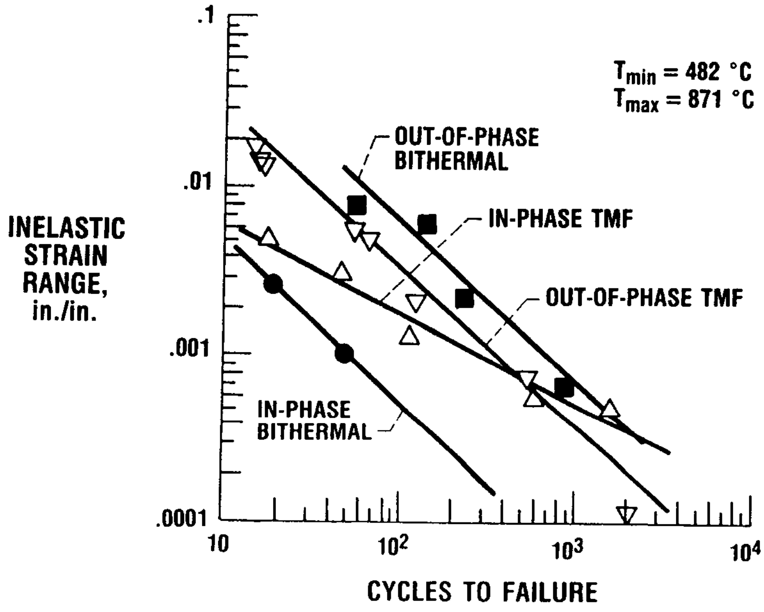
COMPARISON OF TMF AND BITHERMAL FATIGUE DATA

Does the bithermal technique really capture the important effects of a cycle that combines thermally and mechanically induced strains? For one material investigated, B1900+Hf, conventional TMF and bithermal results are similar. As the results show, the bithermal fatigue behavior bounds the TMF results (Halford et al., 1988b). One would expect that bithermal fatigue would result in slightly shorter lives than TMF. However, in this case the slightly longer life of the out-of-phase bithermal fatigue may be attributable to the longer TMF cycle time.

B1900+Hf



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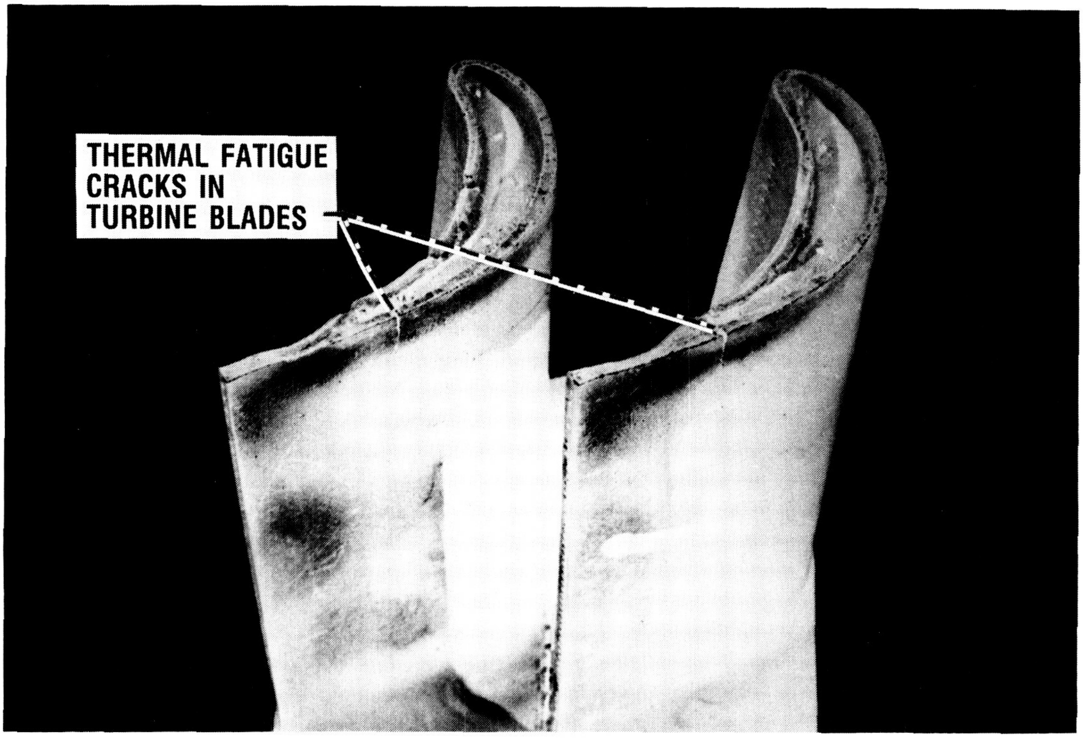
POSTER PRESENTATION

WHAT IS TMF?

Many high-temperature components, such as gas turbine blades, experience both temperatures and mechanical strains that vary with time. Thermal fatigue is the result of constrained thermal expansion in solids undergoing cyclic temperature gradients. Superimposed mechanical loadings may also be involved. The cracks in the pictured turbine blades are a result of thermal fatigue. Thermomechanical fatigue (TMF) is an experimental simplification of thermal fatigue. During TMF a material specimen is subjected to both temperatures and mechanical strains that vary cyclically.



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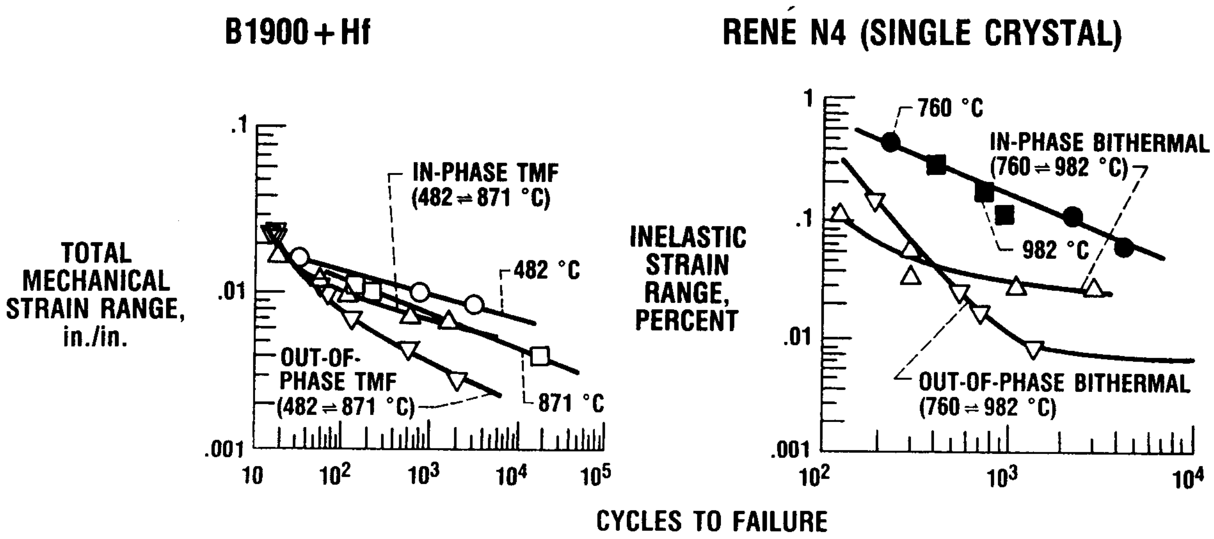
HOW DOES TMF COMPARE WITH ISOTHERMAL LCF?

For some alloys, such as the nickel-base superalloys single-crystal René N4 and polycrystalline B1900+Hf, thermomechanical fatigue has been found to yield significantly lower fatigue lives than does fatigue at either the minimum or maximum cycle temperatures. Major design codes have assumed fatigue at the maximum service temperature to be a conservative design parameter. Consequently most high-temperature, low-cycle fatigue data have been generated under isothermal conditions. This approach has been assumed to be conservative, but it is not.



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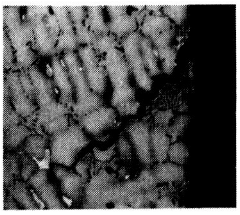
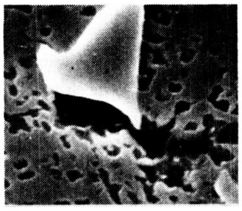
TEMPERATURE-STRAIN PHASING EFFECTS DURING TMF

Not only can thermomechanical fatigue life data vary significantly from isothermal data, but variation in the phasing of the temperature and mechanical strain can also drastically affect the crack initiation and growth mechanisms during TMF. Pictured below is the effect of temperature and mechanical strain phasing on crack initiation and crack growth in Mar-M 200 (Bill et al., 1984).

IN PHASE



CRACK TIP AND CRACK
SURFACE OXIDATION



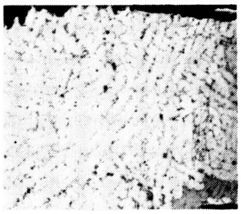
CARBIDE/MATRIX
PULL-AWAY

INTERGRANULAR
PROPAGATION

OUT OF PHASE

BLUNT CRACK TIP AND
LESS OXIDIZED
SURFACE

CRACKING WITHIN
CARBIDES



INTERGRANULAR AND
TRANSGRANULAR
PROPAGATION

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BITHERMAL VERSUS TMF

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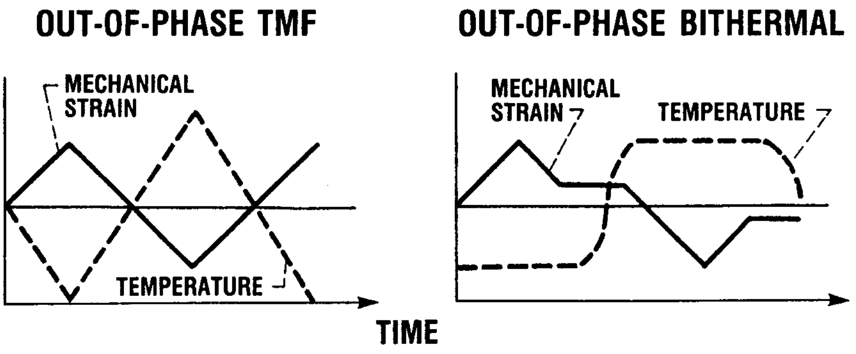
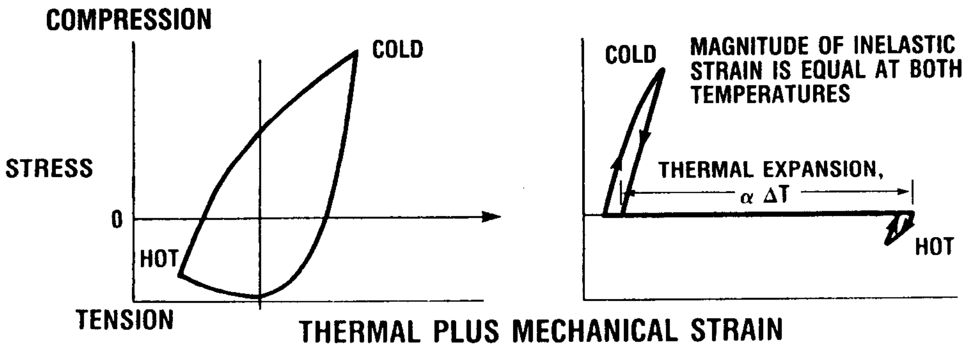


TEMPERATURE AND STRAIN WAVEFORMS



THERMAL PLUS MECHANICAL STRAIN HYSTERESIS LOOPS

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PROS AND CONS OF BITHERMAL CYCLING

The bithermal cycling concept has advantages over TMF cycling that must be balanced against the disadvantages. Both the advantages and the disadvantages are listed below.

ADVANTAGES OF BITHERMAL CYCLING

- TEMPERATURE AND MECHANICAL STRAIN WAVEFORMS CAN BE EASILY SYNCHRONIZED.
- THERMAL-FREE EXPANSION STRAINS CAN BE EASILY SUBTRACTED FROM TOTAL (THERMAL PLUS MECHANICAL) STRAINS.
- NUMBER OF ACTIVE DEFORMATION MECHANISMS CAN BE LIMITED BY PROPER CHOICE OF TEMPERATURES.
- SAMPLES CAN DEFORM AT HIGH ENOUGH RATES TO PRECLUDE CREEP.
- TECHNIQUE CAPTURES EFFECT OF THERMAL-FREE EXPANSION MISMATCH STRAINING BETWEEN SUBSTRATE AND COATING OR OXIDE, OR BETWEEN MATRIX AND FIBERS IN A COMPOSITE.

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DISADVANTAGES OF BITHERMAL CYCLING

- HOLDING AT ZERO LOAD DURING TEMPERATURE EXCURSIONS CAN ALLOW UNDESIRABLE RECOVERY PROCESSES TO OCCUR.
- RESULTS CAN BE MISLEADING IF SIMULTANEOUSLY APPLIED MECHANICAL AND THERMAL STRAINS ARE IMPORTANT TO LIFE.
- THERMAL FREE-EXPANSION MISMATCH STRAINS ARE MORE SEVERE THAN THOSE OCCURRING DURING A TMF CYCLE.

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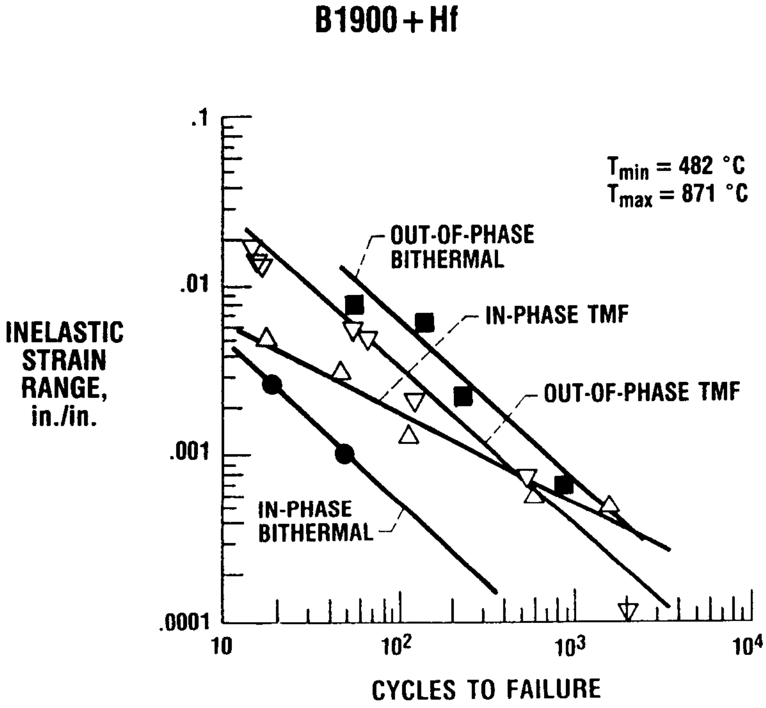

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Bill, R.C., Verrilli, M.J., McGaw, M.A., and Halford, G.R., 1984, "Preliminary Study of the Thermomechanical Fatigue of Polycrystalline Mar-M 200," NASA TP-2280.

Gayda, J., Gabb, T.P., Miner, R.V., and Halford, G.R., 1987, "Bithermal Low-Cycle Fatigue Behavior of a NiCoCrAlY-Coated Single Crystal Superalloy," NASA TM-89831.

Halford, G.R., McGaw, M.A., Bill, R.C., and Fanti, P.D., 1988a, "Bithermal Fatigue: A Link Between Isothermal and Thermomechanical Fatigue," ASTM STP 942, American Society for Testing and Materials, Philadelphia, pp. 625-637.

Halford, G.R., Saltsman, J.F., Verrilli, M.J., Kalluri, S., Ritzert, F.J., and Duckert, R.E., 1988b, "A New Approach to Thermomechanical Fatigue Life Prediction Based on Bithermal Fatigue, Strainrange Partitioning and Unified Constitutive Models," to be presented at the Symposium on Constitutive Equations and Life Prediction Models for High Temperature Applications, Univ. of California, Berkley, CA, June 20-22, 1988.